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KALGOORLIE GEOLOGY RE-INTERPRETED.[1]

J. K. GUSTAFSON AND F. S. MILLER.

ABSTRACT.

The Kalgoorlie Goldfield has produced over 21 million ounces, from gold-pyrite-telluride replacement lodes, mainly in a sill of "younger greenstone" (altered quartz-dolerite, etc.) which, contrary to earlier interpretations, has participated in the regional folding.

The so-called "calc schist," lying beneath the "younger greenstone" stratigraphically, is a series of lava flows whose origin is definitely indicated by pillows and other volcanic textures. Certain banded rocks whose nature had been in doubt are unquestionably carbonaceous slates.

The orebodies occupy fractures that evidently resulted from stress applied to an already complexly folded and fractured rock mass. A cross-fold involving the greenstone contact is one of the factors localizing the more intense fracturing.

Some of the high grade orebodies are pipes at the intersections of fractures. The extremely rich Oroya shoot was a gently raking pipe, localized by shears imposed on a minor fold which involves the immediately overlying quartz-diorite contact.

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[1] The text was written by the senior author who directed the geological investigation. The junior author was responsible for most of the surface mapping and for the preparation of illustrations.

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INTRODUCTION.

THE famous Golden Mile of Kalgoorlie in Western Australia was, between 1888 and 1911, one of the richest and most important gold camps in the world. Annual production, which reached a peak of nearly 1,300,000 ounces in 1903, however, dropped to below 400,000 ounces after 1920. Depression seized the camp, and many mines closed down. The output from this old field is now steadily mounting under the stimulus of a higher price for gold. In 1935, 300,000 ounces of gold were recovered, and the future is bright. Total production from the field is 21,400,000 ounces, and something like £23,600,000 have been paid in dividends.

The Golden Mile has been studied by many geologists. Their somewhat diverse findings were published for the most part in

the Australian technical press, which unfortunately is not sufficiently represented in foreign libraries.

The following article is based on an eighteen months' study in the district for Gold Mines of Kalgoorlie, Ltd. preceded by four years' experience with almost identical rock types in the Porcupine district of Ontario. The excellent record of observed fact left by previous investigators, augmented by talks with observant mining men, greatly simplified this study. In fact, detailed mapping never resulted in materially altering a single rock contact as previously established by Stillwell (16) and his associates on the Golden Mile. Consequently, although some new critical data are presented here, the chief purpose of this article is to re-interpret the major geological structures of the field that have already been established. A new map embracing the north end of the field is presented which differs materially from previous ones.

The reader should be warned that the interpretation of rock structures may appear radical, if not downright heretical, to many of my predecessors (although it coincides almost exactly with Honman's conclusions regarding the geology south of Kalgoorlie (15). The thesis in large part is set forth not as dogma but as a plausible though hitherto neglected explanation of the facts which deserves serious consideration by anyone interested in Kalgoorlie geology. The discussion of lodes and shears is mainly quite orthodox, although the attempt to interpret the mechanics of shearing and the distribution of lodes in this district is a new flight of fancy.

It is manifestly impossible in so short a paper to mention specifically the many earlier observations or to discuss the many detailed points of agreement and difference in points of view. Stillwell has already done this in a comprehensive manner. The attached bibliography includes all the important writings on the subject.

The courtesy of my friends at adjoining mines in generously allowing me access underground, to consult their maps in their offices, and to glean something of their long experience in the

district is hereby gratefully acknowledged. H. J. C. Conolly and H. E. McKinstry were in more or less constant touch with the investigation in an advisory capacity. Their advice and criticism have been most helpful. The Directors of Gold Mines of Kalgoorlie, Ltd. and of Western Mining Corporation, Ltd. kindly permitted publication of this paper.

ROCKS AND ROCK STRUCTURES.

Figure 1 shows the location and geologic setting of Kalgoorlie. Like most other Western Australian goldfields it occurs in a roof

pendant composed chiefly of ancient volcanics, intrusives and sediments embedded in a granite batholith. The ores are prob-

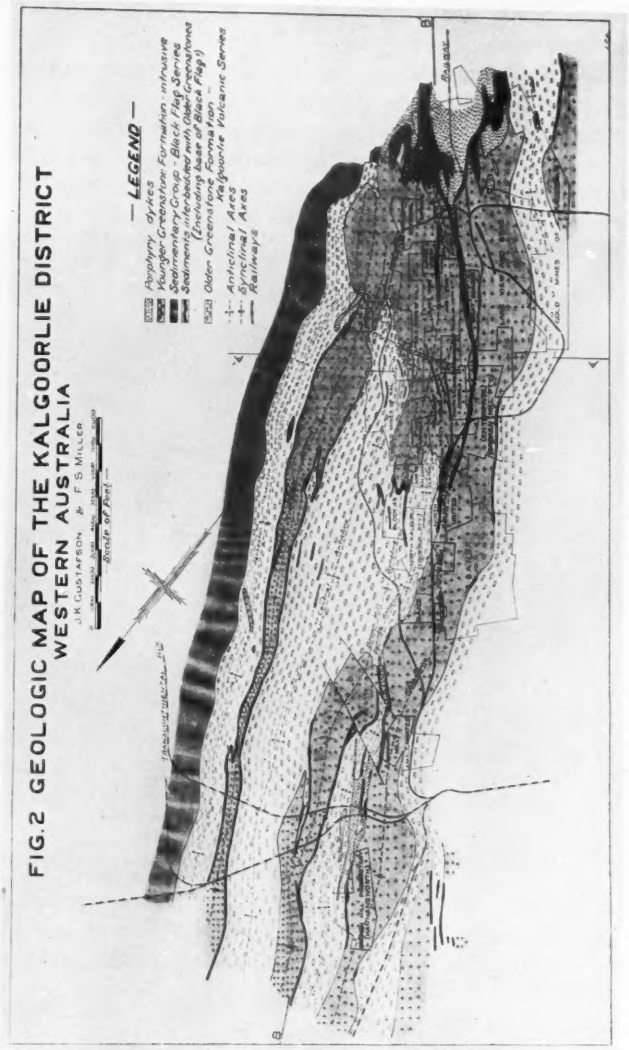


FIG.2 GEOLOGIC MAP OF THE KALGOORLIE DISTRICT
WESTERN AUSTRALIA
J.R. GUSTAFSON & F.S. MILLER
— LEGEND —
Porphyry dykes
Younger Greenstone Formation: intrusive
Sedimentary Group - Black Flag Series
Sedimentary Group - Kalgoorlie Series (Intercalated with Older Greenstones
Older Greenstone Formation (Basic Flag)
Kalgoorlie Volcanic Series
Anticlinal Axes
Synclinal Axes
Railways
Scale of Feet
Boulder
Kalgoorlie

ably related to the granite magma and are presumably pre-Cambrian.

The primary ores are gold-pyrite-telluride replacement lodes occupying sheared zones. They are generally steep, tabular, and lenticular in form. Mineralogically they are similar to the Kirkland Lake ores of Ontario, and like them are classed by Lindgren (18) as hypothermal, although they cannot be far removed from mesothermal. Their mineralogy has been described in considerable detail by Simpson (1, 3), Larcombe (4), and others. The ores are generally oxidised to a depth of 200 feet.

Rock Formations.

The rock formations with which this paper is concerned are the following:

PORPHYRY DIKES	Small intrusive dikes of albite porphyry and "basic porphyrite."
YOUNGER GREENSTONE FORMATION	A large intrusive mass ranging in texture and composition from quartz-dolerite to gabbro to hornblendite, with possibly more femic portions.
SEDIMENTARY GROUP (BLACK FLAG SERIES)	A group of slates, metamorphosed tuffs (?), and grits.
OLDER GREENSTONE (KALGOORLIE SERIES)	An assemblage of fine-grained lavas including one or more interbedded slate members.

These, with the partial exception of the sedimentary group, are identified by virtually all writers, although various names have been applied to them. All belong to what Honman termed the Kalgoorlie series. Regional mapping by Western Mining Corporation geologists suggests the advisability of designating the sedimentary and volcanic series by separate names as indicated in parentheses above, and of omitting intrusives from either category.

Older Greenstone Formation.—This formation has been variously described as a group of lava flows and as a metamorphic tuff; where altered it is commonly referred to as "calc-schist." H. E. McKinstry visiting the field in 1934 was apparently the first to recognise pillows and other undoubted flow features in it. Dr. Miller and I have subsequently mapped this formation over most of the field and inspected it elsewhere. It is a buff to

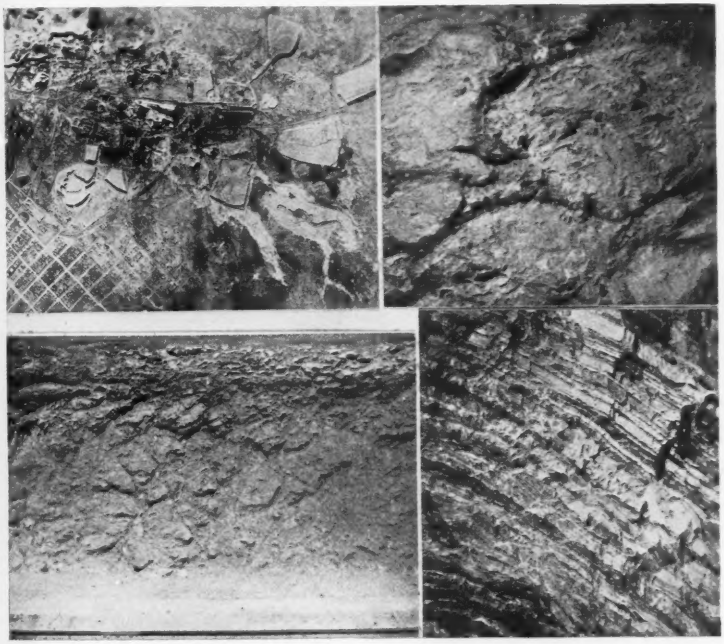


FIG. 3. Air photo of Golden Mile.

FIG. 4. Pillows in Older Greenstone Formation, Brown Hill No. 4 level (Pillows face up).

FIG. 5. Pillows in Older Greenstone Formation in transcontinental railway cut (Top of flow is to left and up).

FIG. 6. Sedimentary bed in Older Greenstone Formation at contact with Younger Greenstone Formation. (Note vertical slaty cleavage.)

greenish fine-grained rock of intermediate composition exhibiting variable degrees of shearing and hydrothermal alteration. It is composed of a series of lava flows, the majority of which in the Brownhill-to-Australia East section are pillow lavas. Pillows are also in evidence on the Ivy workings and in the transcontinental railway cut at the north end. Typical fragmental flowtops and flow breccias are locally in evidence. The pillows are so well formed that facings can be read with certainty in many places. The nature of the rock would instantly be recognised by anyone familiar with the large tracts of pillow lavas in Ontario and Quebec.

In many places in the Older Greenstone formation at or near the contact with the quartz dolerite is a bed of carbonaceous slate. This bed was traced along the contact on the surface in and out of complex folds for a total length of nearly 15 miles. It was mapped in many places underground where similarly it follows the contact through many contortions. Other lenses of slate occur locally between flows in the interior of the formation. The contact bed is of variable thickness and was locally either sheared out completely or cut out by the intrusive quartz dolerite. In other places, however, it is relatively unsheared and possesses perfect sedimentary bedding with normal "slaty cleavage" at an angle to the bedding. In the exposure near the Oroya Shoot on the 1046 ft. level of the Australia lease,[2] sandy layers show repeated gradations in grain size from coarse at the bottom to fine at the top. West facings thus determined check repeated west facings of pillows in the Older Greenstone nearby. Taken in conjunction with drag folds and flow cleavage they support the structural picture here proposed. Locally there are other comparatively little sheared but considerably dragfolded masses of this same sedimentary bed, for example, on the No. 5 Brownhill level.

These sediments manifestly defy explanation as shear zones impregnated with graphite as they have been regarded by most writers. I can see no objection, factual or theoretical, to re-

[2] Plate 2 and 3 of Stillwell, 16, pp. 45, 46.

garding these slates as sediments interbedded with and overlying flows.[3]

Sedimentary Group.—Large areas of "controversial" slates also occur at the south end of the Golden Mile in the vicinity of Slug Hill and The Imperial Mine, in Walsh's Quarry west of Kalgoorlie, and in the Phoenix Brick Pits north and east of Kalgoorlie. Most writers have regarded some at least of these as sediments, although there has been no unanimity of opinion. All of these occurrences, however, have at some time or other been classed as "sheared porphyrite." The Slug Hill sediments are identical in appearance with both the slates in the Older Greenstones and the slates in the "Boulder Dike" and are contiguous with the latter. The sediments in Walsh's quarry are alternating beds of shale, sandstone, and grit. Cross-bedding and grain size gradations within individual beds are sufficiently clearly revealed to permit reading of facings. The beds are unquestionably sedimentary. The rocks in the Phoenix brick pit possess similar characteristics of conclusive sedimentary origin. These sediments all belong to the Black Flag series and were probably separated from the Older Greenstones by the intrusion of Younger Greenstone.

The "Boulder Dyke" is a steep tabular body composed of alternating graphitic slate and albite porphyry with subordinate amounts of material which, as Stillwell points out (16, pp. 47), closely resembles arkose. It is enclosed on both sides by the Younger Greenstone ("quartz dolerite"). The albite porphyry is unquestionably a dike. The slate here is for the most part mashed and much sheared, and evidences of bedding are in many instances obliterated. In a few places, however, bedding is well preserved. A recent diamond drill hole put out east from near Chaffers shaft on the 2650 ft. level traversed the "Boulder Dyke." The core sheds new light on the character of these slates. In some of this core the slate, although comparatively unsheared, shows perfect bedding. Moreover, comparatively unsheared

[3] Honman (15, pp. 22–24) describes similar sediments intercalated with the Older Greenstone flows in adjacent areas.

albite porphyry contains randomly oriented angular inclusions of this material. The conclusion that this material is also sedimentary is to me inescapable. That it represents a sharply in-

FIG. 7. Black Flag sediments at Walsh's Quarry.

FIG. 8. Specimens of drill core from "Boulder Dike," 500 ft. east of Chaffers Shaft, 2630 ft. level. Nos. 1, 2, and 3 show contacts between graphitic sedimentary material somewhat obscured in photo by carbonate veins. Lower right portion of No. 3 is part of angular inclusion of graphitic material in matrix of porphyry Nos. 4, 5, and 6 show typical bedded graphitic sediments.

folded mass of overlying Black Flag sediments intruded by later porphyry is argued in a later discussion of structure.[4]

Younger Greenstone Formation.—This formation is composed of an assemblage of related rock types, some of which apparently are products of magmatic differentiation and others of hydrothermal alteration. Stillwell's classification of these is generally accepted:

(*a*) Uralite quartz dolerite (or epidiorite) . . . the commonest least altered facies.
(*b*) Hornblendite. . . . Magmatic differentiate of (*a*), and
(*c*) Quartz dolerite greenstone . . . a chloritized and carbonated product of (*a*) and the most abundantly occurring type.

The rocks are homogeneous except for alteration differences over large areas and are devoid of any volcanic flow textures. They become fine-grained approaching the Older Greenstones which they intrude. Evidence of chilling is absent only at sheared contacts. Full petrographic description can be found in the literature (1, 2, 3, 4, 9, 10, 11, 16).

Porphyry Dikes.—Small albite porphyry and "basic porphyrite" dikes cut through the other formation mentioned. They have been described in considerable detail by previous writers.

Rock Structures.

Although the distribution of rock types on the Golden Mile has been generally known, and known in considerable detail since

[4] All authors agree that all of these banded rocks look like sediments. Stillwell in discussing those of the Golden Mile proper (16, pp. 43–50) mentions the following arguments for and against their sedimentary origin: FOR: (1) Presence of arkose-like rocks with the slate in the "Boulder Dyke"; (2) usual abrupt change from slates to unsheared igneous rocks; (3) even distribution of minute percentages of carbon; (4) difficulty of accounting for impregnated carbon; (5) development of similar types of slate in dis-similar types of igneous rocks; (6) low alkalies and lime in proportion to the alumina showing a considerable excess of alumina over molecular proportions necessary for feldspar. AGAINST: (1) Occurrence as bands within wide belts of igneous rocks; (2) frequent and persistent association with porphyries; (3) difficulty of conceiving their origin as sediments.

The arguments *against* disappear if the structural interpretation presented here is accepted.

Stillwell's excellent maps were published, there has been little attempt to explain the structures in evidence. A tacit assumption has prevailed that the present rock pattern resulted simply from the exposure of intrusive contacts. I hope to present conclusive evidence (1) that these contacts in large part are folded contacts, and (2) that a recognition of folding is important to the broad understanding of lode distribution.

The Older Greenstone-Younger Greenstone Contact.—The following observations support the contention that (*a*) the Younger Greenstone formation was intruded as a sill or laccolith (and not as a dike as hitherto assumed) and (*b*) that following this intrusion the rocks were squeezed and folded.

(1) The presence of ubiquitous graphitic slate between flows of the Older Greenstone at or near the intrusive contact shows that the Younger Greenstone everywhere occupies approximately the same stratigraphic horizon.

Stillwell's mapping (and mine) shows that "off-sets" and "benches" in the contact are not due to faulting as advocated by Larcombe and MacLaren. The fact that the slate member bends around these pitching ridges and troughs shows them to be minor folds on the flanks of the larger folded structure.

(2) Moreover, the general westerly dip of the contact on the eastern limb of the main syncline coincides roughly with the westerly dip of the slate member and of west-facing pillows in the Older Greenstone flows. East-facing pillows also occur on the eastern flank of the anticline in the Ivy lease and in the transcontinental railroad cut at the north end. Thus the Younger Greenstone conforms to the folds in the older rocks.

(3) The epidiorite is obviously a moderately shallow seated intrusive. (I have mapped lava flows of almost identical texture, appearance and composition in the Hollinger Mine, Canada.) Such intrusives notoriously cut across pre-existing contorted structures and never (to my knowledge) follow them faithfully. On the other hand, sills and laccoliths commonly penetrate between members of a flat sedimentary or volcanic series.

On the basis of this evidence, I conclude that the Younger Greenstone is a sill or laccolith intruded when the Older Greenstones were essentially flat-lying. Stillwell was not unaware of this possibility and refers to the rock mass in several instances as a "dyke or sill." There are, to be sure, detailed instances where

the Younger Greenstone apparently cuts across structures in the older rock. The epidiorite, however, is a strong homogeneous rock and behaved competently under regional stress. The pillow lavas on the contrary, being relatively weak and incompetent during folding, crumpled and sheared to a greater extent. Particularly was this true of portions of the formation adjacent to its more resistant neighbor. This differential response to compressive stresses, together with the obvious shearing that has taken place along the contact, accounts, I believe, for the minor discordances of structure.

The Kalgoorlie Syncline.—The major structure of the mining area of the Golden Mile is a flat, south-pitching, syncline containing a core of Younger Greenstone flanked and underlain by Older Greenstone. North of the Golden Mile there is a change in pitch as shown by the behavior of the Younger Greenstone-Older Greenstone contact. (Dragfolds in the sediments in the Phoenix brick pits also pitch north.) The warped pitch line is shown diagrammatically in Fig. 9.

Much of the evidence for this syncline on the eastern side of the field has been presented. There are no mine workings in the Older Greenstone on the western side of the fold and but few outcrops. A recent diamond drill hole, however, put down on the Ixion Lease passed through successive lava flows and finally penetrated the Younger Greenstone. The evidence was not conclusive but highly suggestive that these flows face east. (Evidence: several chilled bottoms grading coarser and then passing into fine-grained fragmental flow tops.) The syncline occurs on a deep infold in the larger predominantly anticlinal fold embracing the Kalgoorlie field, as shown by the accompanying diagrams.

Evidence of Slates at the South End.—On the south end of the field on the surface and in the Imperial mine, the large body of slate (hitherto mapped as "porphyrite") shows numerous south-pitching dragfolds as well as flow-cleavages indicative of south pitch. This slate was therefore definitely involved in the major folding. Either it

FIG.9 GENERALISED LONGITUDINAL SECTION — KALGOORLIE — WESTERN AUSTRALIA

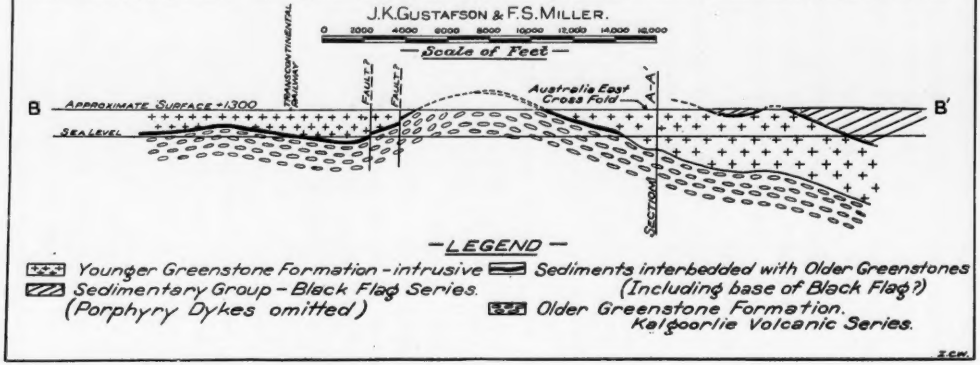


FIG.9A. TRANSVERSE SECTION A-A — KALGOORLIE DISTRICT — WESTERN AUSTRALIA
SHOWING DEVELOPMENT OF PRESENT GEOLOGIC STRUCTURE

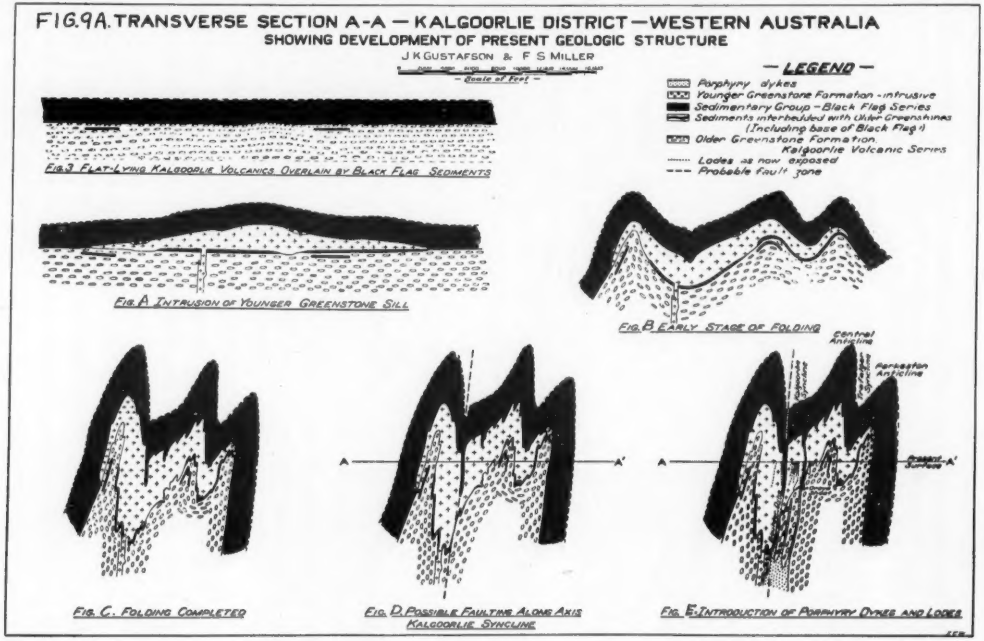


FIG.9A. TRANSVERSE SECTION A-A — KALGOORLIE DISTRICT — WESTERN AUSTRALIA
SHOWING DEVELOPMENT OF PRESENT GEOLOGIC STRUCTURE
J.K.GUSTAFSON & F.S.MILLER
— Scale of Feet —
— LEGEND —
Porphyry dykes
Younger Greenstone Formation - intrusive
Sedimentary Group - Black Flag Series
Sediments interbedded with Older Greenstones (Including base of Black Flag)
Older Greenstone Formation
Kalgoorlie Volcanic Series
Lodes as now exposed
Probable fault zone
FIG.A. INTRUSION OF YOUNGER GREENSTONE SILL
FIG.B. EARLY STAGE OF FOLDING
FIG.C. FOLDING COMPLETED
FIG.D. POSSIBLE FAULTING ALONG AXIS KALGOORLIE SYNCLINE
FIG.E. INTRODUCTION OF PORPHYRY DYKES AND LODES
Central Anticline
Perseverance Anticline
A
A'

(*a*) Was deposited unconformably upon both Older and Younger Greenstones following an interval of erosion, or

(*b*) Originally overlay the Older Greenstone and was separated from that formation, when still essentially flat-lying, by the intrusive sill of epidiorite. The sill was limited in its extent, and the slates are in contact with the Older Greenstone wherever the sill is missing.

I believe the second hypothesis is more in keeping with the facts. (The quartz dolerite appears to be chilled against the overlying slate in Lake View South.) Thus there was a period of vulcanism resulting in a thick accumulation of lava flows (sub-marine if the orthodox interpretation of pillows be accepted.) Towards the end of the period, the volcanic activity became intermittent and sediments collected during intervals. Finally, it stopped for a period sufficient at least for a considerable thickness of muds and sands to be deposited. Later, magma emerging through a crack in the volcanic pile forced its way between the overlying sediments and the underlying flows and there solidified. Folding eventually gave us our present structure.[5]

The "Boulder Dyke."—This important structure separates the two major lode systems of the Golden Mile. It marks the axial plane of the Kalgoorlie syncline. To my mind it began as a sharply infolded double limb of the overlying slate. In the later stages of folding, as the structures tightened, it became so sheared and attenuated that it lost the appearance of a syncline and became in reality a graphitic shear zone. The close approach to it in depth of the Older Greenstone contact on the east limb of the main syncline suggests that later normal faulting also occurred here (Fig. 8). Finally, the albite porphyry found this zone of weakness a place of easy access.

A similar infold of slate on a smaller scale occurs on the Lake View, Lake View South and Lake View South Extended leases.

[5] If such a syncline as this exists, the Older Greenstones lie vertically below the Western Lode System. Since the Eastern Lode System has practically bottomed where it met this formation, the Western Lode System may be expected to do the same. If my judgment is correct, however, there is no expectancy of this happening for some thousands of feet below the present lowest levels.

In the Lake View South the syncline of slate bottoms between the No. 2 and No. 3 levels.

Minor Folds.—Four folds on the flank of the Kalgoorlie Syncline deserve mention:

(1) The Oroya Shoot fold (in which were localized flat shears that provided access for the ore solutions that formed the famous Oroya Shoot).
(2) The Paringa anticline and its counterpart the Brownhill syncline, which is dying out gradually southward in depth.
(3) The Central anticline.
(4) The Australia East cross-fold.

The first three are perfectly normal south-pitching structures revealing rotational drag in accord with the major structure. The fourth, however, is a structural anomaly showing sudden reversals of pitch. The Oroya Shoot fold approaching it on a normal pitch of 25°–30° suddenly flattens out to 0°, and the ore shoot accompanying it dies. I can account for this pucker only by supposing an earlier period of gentle folding that produced an anticline with an east-west axial trend. Such a fold squeezed end-on by later compressive forces would produce a structure similar to the one in question. The cross-fold is itself drag-folded. Regional cleavage, flattened pillows, and similar features in this structure retain their normal orientation parallel to the axial plane of the major folds and further emphasize that the cross-fold is the older. The resistance offered by this knot in the country caused the axial plane of the Kalgoorlie syncline to be bent in the later stages of folding. This bending is clearly revealed by the outline of the " Boulder Dyke."

This cross-fold may have been extremely important in determining the position of Kalgoorlie lode systems. Other differences of pitch in the district may be due to other old cross-folds

Figs. 3 to 8.—This series of sketches illustrates the evolution of Kalgoorlie structures according to the theory under discussion. It is of course impossible from the meagre data to determine the depth of synclinal troughs.

Criticism of Structural Interpretation.—From the few discus-

sions that I have had with geologists regarding my views of the structure just presented, I anticipate the following objections:

(1) The epidiorite in many places is a massive rock too little sheared and schisted to have suffered the folding history ascribed to it.

(2) A long attenuated fold like the supposed "Boulder Dyke" syncline (if it is not a geological monstrosity) is exceedingly unlike the other folds described. Moreover, the mechanics of formation are difficult to visualize.

(3) If the banding in the slates of the "Boulder Dyke" is indeed original bedding, it could not have survived the intense shearing necessarily accompanying the development of such a structure as is pictured here.

As regards item (1), the epidiorite is almost identical in its physical and chemical properties with pre-Cambrian lava flows in the Hollinger and adjacent mines of the Porcupine district in Canada. Nevertheless, these flows are involved in equally tight folds, the validity of which cannot be questioned.

As for item (2), the graphitic slates and tuffs, closely resembling these in Kalgoorlie and which are interbedded with the Porcupine flows, are squeezed into analogous structures. Soft sediments caught between jaws of massive igneous rocks during folding act like grease. They are squeezed into far tighter and more attenuated structures than their massive neighbors. They may be dragged and literally squirted into shears for considerable distances (19, 20).

As for retention of bedding in close sheared folds (Item (3)), both the sediments of the Porcupine district and those of the Homestake mine at Lead, South Dakota (21, 22, 23, 24), which have undergone equally severe squeezing, eloquently testify that this objection is invalid.

Our map of the north end of the field differs radically from Feldtmann's (11). Many of the rocks here have suffered severe hydrothermal alteration with resulting change in grain size and composition; others are highly oxidized and difficult to classify. We believe that Feldtmann in some instances mapped phases of similar alteration across formation boundaries. We recognise pillows in two places where altered Younger Greenstone was previously indicated.

LODES AND SHEARS.

The Lode Systems.

There are two distinct lode systems in Kalgoorlie, separated by the "Boulder Dyke." Although generally similar, each has certain individual characteristics.

In a broad way, these may be compared as follows:

Western Lode System

(1) Consists of fewer lodes but larger ones which are more regular and persistent.
(2) Contains more numerous large, regular ore bodies owing to (*a*) the regularity and persistence of the lodes and (*b*) the more even distribution of gold within them.
(3) Is confined, so far as known, to the Golden Mile proper.
(4) Lodes considerably more disturbed by post-ore faulting.

Eastern Lode System

(1) Contains some large persistent lodes but is characterized rather by swarms of smaller lodes and pipe-like ore shoots which present a most complex and irregular pattern.
(2) Extremely uneven distribution of gold within the lodes with low-grade stretches and numerous locally enriched portions of great value.
(3) Continues intermittently for 3 miles north of the richly productive section in the Golden Mile.
(4) Lodes on the whole less disturbed by post-ore faults.

Relation to Major Rock Structures.

The "Favorable" Quartz Dolerite.—An overwhelming percentage of the productive lodes are confined to the quartz-dolerite of the Younger Greenstone formation [6]—a fact first clearly enunciated by Maclaren (2, 5). Although individually important discoveries will continue to be made in the "unfavorable" Older Greenstone, there is no reason to doubt that this basic generalization, like insurance statistics, will continue to apply to the

[6] The hornblendite occurs only on the western side of the Golden Mile and contains no known ore bodies. This tough massive rock apparently transmitted shearing stresses to the weaker quartz-dolerite without itself yielding.

aggregate. Lode after lode of the Eastern Lode System has died in depth where it encountered the Older Greenstone contact, and the bottom of others can be predicted with fair accuracy. Fortunately, there remains abundant room in unexplored portions of the quartz-dolerite for continued discoveries of new ore to sustain production for many years.

Nevertheless, the northern extension of the main belt of shearing of the Eastern Lode System, where it passes into the Older Greenstones of the Paringa anticline, contains important ore bodies. Experience has shown that ore bodies in the Older Greenstone where they do occur are apt to be one of two kinds: (*a*) small discontinuous pipes of rich ore, or (*b*) extremely low-grade tabular bodies.

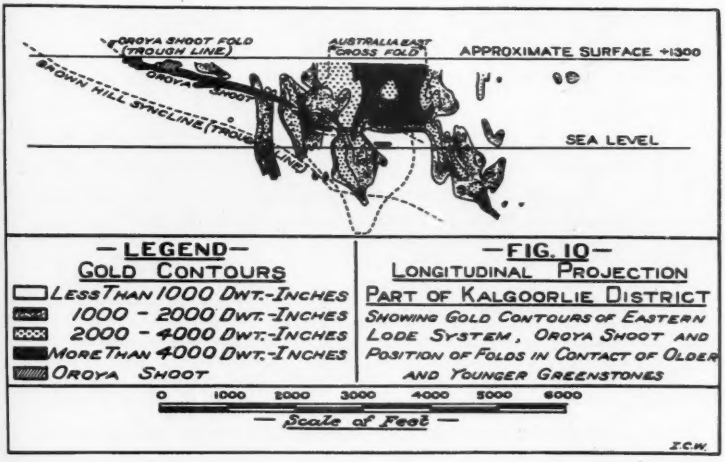
The quartz-dolerite and "calc schist" appear to have behaved differently under stress. The quartz-dolerite was generally more brittle and yielded by means of strong, well-defined, and through-going shears. The pillow lavas, on the other hand, were probably weaker and characteristically failed along many small discontinuous planes of movement distributed throughout the rock. Later ore solutions thus found in the quartz-dolerite strong channel-ways through which to flow. On the contrary, in the "calc schist" they encountered numerous small pathways leading nowhere. Active flow was inhibited, and on the whole feebler and more disperse mineralization resulted. Locally, conditions were favorable for ore deposition, and at these places isolated ore bodies developed. Only the stronger shears of the district were capable of preserving their identity for any distance into this rock before the stresses producing them became dissipated along many subsidiary fractures.

Project the southern mass of overlying slates northward up the pitch and it is seen that the quartz-dolerite of the Golden Mile was covered by slate some 2,000 or 3,000 feet above the present erosion surface. It is doubtful if the lodes penetrated this cover of slate to any appreciable extent, for it even more than the Older Greenstones would be expected to have behaved plastically under stress and to have inhibited the formation of strong open channel-

ways within it. Just under the slate, however, there may have been enrichments due to the concentrated flow of ore solutions beneath this impenetrable capping. Indeed, the falling off in grade and quantity of ore with depth may be in part due to the increasing distance away from the benevolent influence of this contact.

In addition to the concentration of ore in one formation, rock structures appear to have exacted a major control on the localization of lodes in the following instances.

The Australia East Cross-Fold.—The richest portion of the Eastern Lode System is opposite the Australia East cross-fold. Figure 10 illustrates this seeming correlation between abundance


OROYA SHOOT FOLD (TROUGH LINE)
AUSTRALIA EAST CROSS FOLD
APPROXIMATE SURFACE +1300
OROYA SHOOT
SEA LEVEL
— LEGEND —
GOLD CONTOURS
LESS THAN 1000 DWT.-INCHES
1000 - 2000 DWT.-INCHES
2000 - 4000 DWT.-INCHES
MORE THAN 4000 DWT.-INCHES
OROYA SHOOT
— FIG. 10 —
LONGITUDINAL PROJECTION
PART OF KALGOORLIE DISTRICT
SHOWING GOLD CONTOURS OF EASTERN LODE SYSTEM, OROYA SHOOT AND POSITION OF FOLDS IN CONTACT OF OLDER AND YOUNGER GREENSTONES
0 1000 2000 3000 4000 5000 6000
— Scale of Feet —
J.C.W.

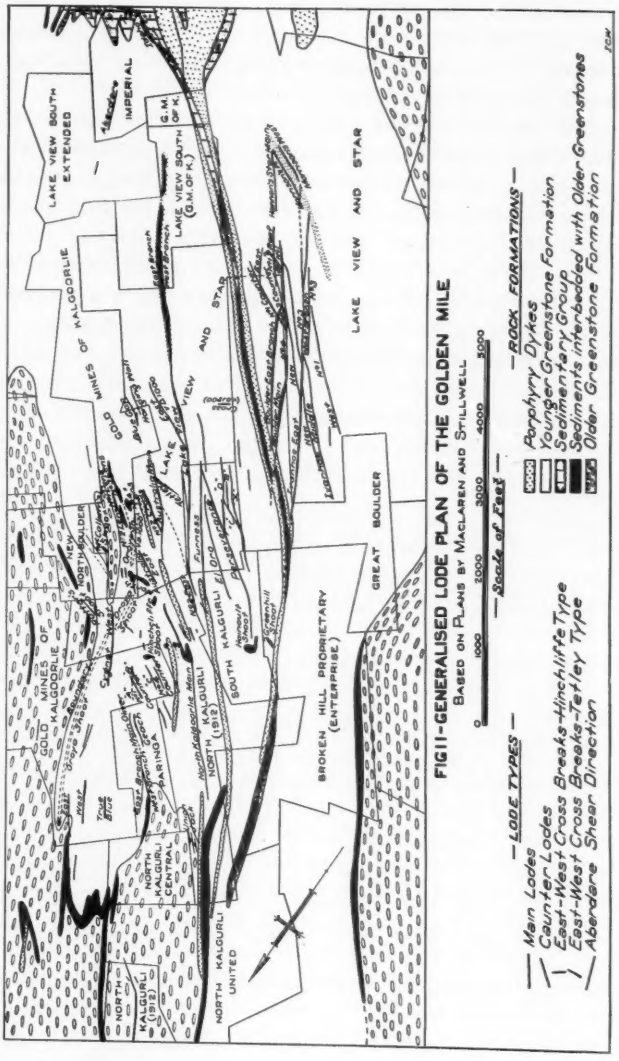
of gold and proximity to this structure. This "knot" in the country apparently allowed shearing stresses to find their fullest expression about it, much as the splitting of a pine board is influenced by knots in it. In time ore solutions found this a region of easy access. The gold contour pattern of the Western Lode System is, nevertheless, surprisingly similar (but with the bottom of most abundant gold at a lower elevation) and cannot be cor-

related with any analogous structure. Was the Western Lode System, however, also localized by this cross-fold on the western flank of the Kalgoorlie syncline, but was the cross-fold faulted—offset to the south—by movement along the plane that is now the "Boulder Dyke"? (Such movement would have taken place prior to the development of lode-shears.) If so, it would give an answer to the perplexing question, "why are the lode systems precisely where they are?" Unfortunately, the Younger Greenstone-Older Greenstone contact is not sufficiently exposed in the critical area to give the answer.

Porphyry Dikes.—In a general way, there is a correlation between the distribution of porphyry dikes and of lodes. In detail, individual lode shears have been deflected by dikes, which in some cases they follow for considerable distances; some ore shoots occur at dike contacts, particularly at the ends of dikes (16, pp. 66) in a way suggesting concentration of shearing at these places.

Main lodes of the Western Lode System (so far as is known) stop abruptly northward where they encounter the "Boulder Dyke," although very little search has been made for continuations beyond. (Main lode shears may even fault the "Boulder Dyke" as suggested in Fig. 11.)

The Oroya Shoot (and Others).—The famous Oroya Shoot is a case of shearing localized by a normal minor fold in the rocks. It is, however, a freak without parallel among ore bodies in the district both because of its unique geologic character and its remarkable continuity and richness. (Production from this ore shoot alone is estimated at nearly 2,000,000 ounces.) During the shearing of the district, a flat, south-pitching minor fold at the Older Greenstone-Younger Greenstone contact on the eastern flank of the main Kalgoorlie syncline proved to be a locus of weakness. Two flatly west-dipping shears connected by a thin almost horizontal shear developed in this structure. The graphitic hanging wall shear was largely confined to the carbonaceous slate member at the top of the Older Greenstone formation. Ascending mineralizing solutions impregnated this crushed zone


LAKE VIEW SOUTH EXTENDED
IMPERIAL
G.M. OF K.
LAKE VIEW SOUTH (G.M. OF K.)
GOLD MINES OF KALGOORLIE
LAKE VIEW AND STAR
NORTH BOULDER
LAKE VIEW
NORTH KALGURLI (BLOCK 14)
NORTH KALGURLI CENTRAL
NORTH KALGURLI (BLOCK 10)
NORTH KALGURLI UNITED
SOUTH KALGURLI
BROKEN HILL PROPRIETARY (INTERPRISE)
GREAT BOULDER
FIG11-GENERALISED LODE PLAN OF THE GOLDEN MILE
BASED ON PLANS BY MACLAREN AND STILLWELL
Scale of Feet
0 1000 2000 3000 4000 5000
LODE TYPES
Main Lodes
Counter Lodes
East-West Cross Breaks-Hinchliffe Type
East-West Cross Breaks-Perkey Type
Aberdare Shear Direction
ROCK FORMATIONS
Porphyry Dykes
Younger Greenstone Formation
Sedimentary Group
Sediments interbedded with Older Greenstones
Older Greenstone Formation

to form a flat pipe of ore almost continuous for a length of 4,000 ft. Probably at no other place in Kalgoorlie did such a coincidence of favorable rock structure exist, much less happen to be in the pathway of later auriferous solutions.

Where the fold pitches into the Australia East cross-fold its pitch flattens out and even becomes reversed temporarily before proceeding on its normal course. The shears, however, continue without serious interruption and pass beneath the fold into the body of the "calc schist" where the lode dies.

In the Idaho lease (Imperial), mineralization is concentrated at the flatly pitching folded contact between the quartz-dolerite and the overlying slate. Union Jack lodes in the aggregate appear to pitch with the Paringa anticline.

In general, however, neither individual lodes nor groups of lodes continue down the flat southerly pitch of folds.

The Shear Pattern—Structural Lode Types.

Maclaren (2) early recognised the fundamental shear pattern in the Younger Greenstone which governs the distribution of lodes (and dikes) within the systems. He recognised and named two main and one subordinate directions:

(1) Main lodes striking predominantly N. 30° W. to N. 50° W. and dipping for the most part to 75° W. to vertical (Local steep easterly dips).
(2) Caunter lodes generally striking N. 50° W. to N. 60° W. and dipping as a rule slightly flatter than the main shears.
(3) East-west cross-breaks (tension openings?) steeply N. or S.

Main and Caunter Shears.—The main shears are the dominant ones and commonly offset the others. They are roughly parallel to the axial plane of the folds. The caunter shears are generally less persistent and in places terminate at both ends against main shears. Lodes within these two have contained the great preponderance of the gold in the camp. And a majority of the richer ore shoots occur at intersections between the main and caunter lodes. These intersections pitch steeply south.

The shear pattern in the Older Greenstone formation is closely analogous, but in the Union Jack lease, at least, is a suggestion of important differences. Here the caunter (?) lodes dip much more flatly than those in the Younger Greenstone. They are probably faulted by the main shears, and probably, in this instance at least, only the flat caunter shears contain important ore bodies. This set of conditions requires greater emphasis on vertical exploration than is customary. The Crœsus Pty. lode, however, occupies a strong main shear.

The main-caunter shear pattern just described can be seen on a small scale within individual lodes. A lode, for example, following a main shear may leave it and make across to an adjacent parallel shear along a caunter break which acts as a connecting link.

East-West Cross Breaks.—These are much less common than the main and caunter shears but have, nevertheless, been responsible for a number of rich pipes of ore in the Eastern Lode System. Most of these ore pipes occur at intersections with main or caunter lodes. They are faulted by main and possibly by caunter shears. Individuals do not appear to have great lateral extent, although zones of them may have. For example, the following ore-pipes line up roughly from east to west: Hinchcliffe shoot (Iron Duke lease), steep lenses of ore on Kalgurli lease, Hainault shoot (Hainault lease) and Greenhill shoot (Enterprise lease). The last two definitely occur on the same east-west cross-break.

There appear to be two types of cross-breaks resulting in ore-pipes distinguished chiefly by differences in orientation.

(*a*) Hinchcliffe type. . . . Strike N. 40° E., dip nearly vertical to north or south (Examples: Hinchcliffe shoot, Kalgurli ore pipe, Hainault shoot, South Kalgurli cross-lode). Stillwell's plans suggest others apparently associated with basic dikes of the same orientation (16).

(*b*) Tetley type. . . . Strike N. 80° W., dip, 60°–70° south (Examples: Tetley lode(s), McCallum shoot, North Lode, rich tribute near Pomeroy shaft in Oroya North Block).

The extensions of some of these, particularly where they would intersect with known shears, are worth exploring.

East-west cross breaks are, however, but one expression of an important east-west structural influence. At least five major east-west belts characterized not only by the presence of east-west cross-breaks but also by the greater number, size, and richness of main and caunter lodes can be recognised crossing the eastern lode system.

Aberdare Shear Direction.—In the north end of the field, as shown by Feldtmann's map (10), are several well defined barren shears that strike approximately N. 3° W. to N. 20° W. In the Golden Mile proper the Aberdare Lode has approximately this same orientation as have occasional parallel pre-mineral shears in Australia East (and perhaps elsewhere). Caunter lodes do not cross these shears in Australia East.

Other Pre-Ore Shears.—Other pre-ore shears greatly complicate the operating problem. Flat ore bodies in the Younger Greenstone are rare, although there is one in the North Kalgurli lease. Rutter's shoot in Oroya North Block and Australia East is another, although the larger portion of this lode occurs in Older Greenstone. It may occupy a "normal" caunter shear of that formation which extends a short distance beyond the contact.

Rare strike faults roughly parallel to main shears and dipping predominantly 65° to 80° east (to 70° W.), are known to cut off some lodes on the eastern side of the field. The No. 2 cross lode, a strong caunter lode in the Australia lease, is for example on all levels terminated abruptly southward by such a fault.

In South Kalgurli, Enterprise, and Crœsus Pty. these faults are fairly numerous. Some of them in Crœsus Pty. show movement of more than 100 ft. Striation and mullion structure where visible on the fault planes generally pitch south at 15 to 30 degrees. Commonly, the east side has moved north and up, but there are important exceptions where the reverse is true. Many of these fault planes are feebly mineralized, and a few contain payable lodes. Others are completely barren. Probably all were

originally pre-ore in age. On some, post-ore movements may have occurred.

Pre-ore slides or "heads" occur everywhere. Many of them, virtually indistinguishable from the rest, play an important part in localising values. The majority are fairly inconspicuous, dip flatly west, and cannot be traced for any distance. Values in a drive may suddenly increase from 3 dwts. to 10 dwts. or more where one of them is encountered—or payable values may cut out as quickly; and yet the lode suffers little visible change. In other cases, the mineralization spreads out on the flat slide and appears to stop beyond it. Horizontal zones of jointing have much the same effect. Consequently, a vertical lode may consist of alternate horizontal layers of rich and lean ore. Many good drives have yielded poor leading stopes and have been abandoned only to be stoped eventually at a profit by a more adventuresome management or by one with a rich stope neaby to use as a "sweetener." These influences are important to watch in development drives and stopes, yet rarely appear on a large enough scale to guide exploration.

Mechanics and Sequence of Shearing.—Granted the folded structure described in Part I, the fact that the shear pattern is essentially the same (instead of reversed) on both sides of the Kalgoorlie Syncline precludes the likelihood that the main shear pattern was developed during folding. That it was initiated prior to dike intrusion is shown by the kindred pattern of dike and lode distribution. Post-dike movements accentuated and but slightly modified the original pattern. The dikes themselves were somewhat sheared and the "Boulder Dyke" may be faulted by the Ivanhoe East and No. 4 lode shears (or so the "branching tongues" of dike (Stillwell (16), p. 32) may be interpreted).

The lode-shear pattern was thus superimposed on a heterogeneous and folded group of rocks that retained many unevenly distributed strains and partially unrelieved stresses accumulated during folding and after. Probably movement on the plane which is now the "Boulder Dyke" greatly relieved the stresses imparted to the mass of quartz dolerite west of that structure

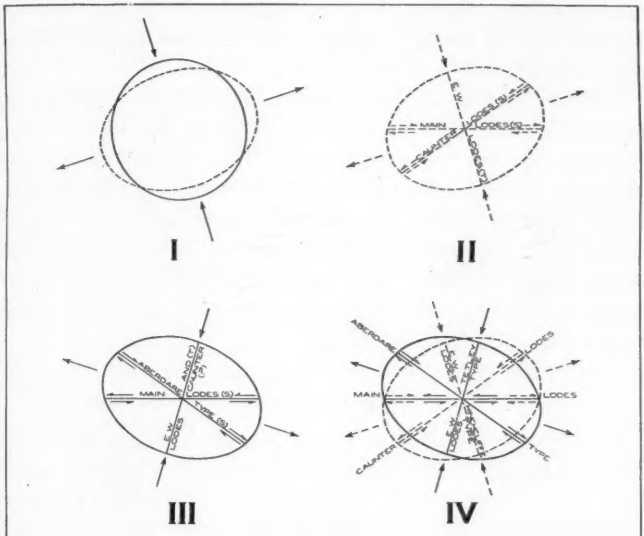
during folding, protecting it in some measure from the severe internal movement suffered by the mass of similar rock to the east. At a much later date when the region was again subjected to stress, a fairly regular shear pattern developed in the comparatively homogeneous western rock mass. East of the dike, on the other hand, where stresses found a rock containing countless eddys and currents of old weaknesses, the normal pattern was greatly modified. More numerous and shorter breaks occurred in the compromise between old shears and new, and gave rise to the numerous small pipe-like ore bodies that are found here.

The shear pattern of the Golden Mile is distinguished from that of the north end of the field in that fracturing on the Golden Mile was predominantly by means of main shears and caunter openings, whereas farther north it was by means of main shears and subordinate shears (Aberdare direction) of which the latter are barren. The caunter direction here is very poorly expressed. Numerous small quartz veins may be the equivalents of the east-west cross-breaks of the Golden Mile.

As in so many other pre-Cambrian ore deposits, an attempt to apply the strain ellipsoid here is like trying to force a six-fingered hand into a five-fingered glove. When main shears, caunter shears, and east-west cross-breaks are alone considered, the strain ellipsoid offers a fairly reasonable explanation of the fracture pattern. (Figure 12, II, illustrates this case in mind.) Difficulties are: (1) The observed offset of caunter lodes by main lodes is in a direction opposite to that required by theory; (2) it fails to account for the Aberdare shear direction; and (3) the great abundance of caunter lodes occur in a belt crossing both lode systems in a direction parallel to the Aberdare shear direction, giving in effect an *en echelon* arrangement of the two lode systems. (That this arrangement alternatively may be due to offsetting of the Australia East cross-fold rather than to any requirement of the lode fracture pattern was suggested above.) On a smaller scale, however, some of the east-west cross-breaks ((*b*) type) are similarly disposed *en echelon* parallel the Aberdare shear direction. For example, Tetley lode, North lode, and the tributors' lode near

the Oroya North Block shaft are so aligned. They suggest fracture by means of tension cracks along a shear direction—a common feature of field and laboratory experience.

Re-orienting the strain ellipsoid to remove these difficulties gives rise to others. In the alternative set-up, indicated by Fig. 12, III, major objections are: (1) The angle between main shears



and caunter tension openings is too flat; (2) the divergence in strike as between caunter openings and cross-breaks, both of which must be regarded as tension phenomena, is too large; and (3) there is no difference in appearance of main and caunter lodes.

It should be borne in mind that the final lode-shear pattern was a compromise between old strains and new stresses and that continued pressure after rock failure may have caused movement on both shears and tension cracks already formed, re-orienting some of them and obliterating any visible distinction between shears and tension openings in others. There may even have been two periods of movement under somewhat differently oriented stresses. Thus Fig. 12, II, may represent the first period and Fig. 12, III, the second. Figure 12, IV, illustrates the effect of combining the two.

Post-Ore Faults.—Lodes in the western belt are considerably disturbed by flat faults, most of which are presumably post-ore. The majority, but not all, dip west. Their displacement is not large, but they materially add to development and mining costs. Stopes must be carried up through barren intervals between faulted lode segments. Shrinkage stoping can seldom be employed in their vicinity. Steep post-ore strike faults also occur. Many of these, however, originated as pre-ore breaks along which there has been repeated movement.

SOURCE OF ORE BEARING SOLUTIONS.

The gold bearing solutions probably came from the underlying granite batholith, as did the porphyry dikes at a slightly earlier date. Shears within the "Boulder Dyke" may have extended to considerable depth. Possibly they were the openings through which ascending solutions reached the favorably prepared Younger Greenstone. I visualize the ore solutions as entering the quartz-dolerite on the western side of the field and as spreading through the shears above the Older Greenstone contact into what is now the Eastern Lode System.

ORE FINDING.

The problem of ore-finding in Kalgoorlie is two-fold. It includes (*a*) the search for new lenses of ore still existing in the complicated network of intersecting shears just described. Such

a search intelligently pursued requires the recognition of inconspicuous breaks in the country and of subtle changes in the rock and ore and finally their assemblage into a clear three-dimensional picture. Few districts reveal such a close dependence of values upon such inconspicuous features or reward to such an extent the continual close observance of these features in development and stope faces. The greatest strain on careful observation is in isolating the significant details from the many. The geometry of projecting the complicated data is not always a simple matter. Exploration also includes (*b*) the search for totally new orebodies beyond the assumed confines of productive ground. The gamble here is one of long risks and high stakes. It offers scope for the best geological thinking.

I have recorded my observations and my guesses in a general way as to the geology of this field in the hope that my friends in Kalgoorlie will derive the stimulus to correct or expand these into an increasingly truer picture of ore occurrence.

SUMMARY OF GEOLOGIC HISTORY.

The pre-Cambrian history of the immediate district may be reconstructed as follows:

1. Volcanic period resulting in lava flows of the Older Greenstones interrupted by occasional sedimentation; period merging into
2. Sedimentary period providing sediments of an overlying series.
3. Intrusion of Younger Greenstone as sill or laccolith between Older Greenstones and later sediments.
4. Deep burial by later formations unrecorded in district (Folding is of deep-seated type indicating near approach to conditions of rock flowage).
5. Gentle folding on E.-W. axes (Evidence of Australia East cross-fold and changes of pitch).
6. Strong folding on N.W.-S.E. axes resulting in major folds.
7. Uplift probably accompanied or followed by shearing and faulting which established the dominant lode and dyke

pattern. (Porphyrite dykes are relatively shallow intrusive types and followed well developed shears.)

8. Intrusion of porphyrite dykes, the upward expression of deep invasion by a granite magma.
9. Renewed shearing and reopening of old shears providing channelways for ore solutions.
10. Ore deposition by solutions emanating from granite batholith below.
11. Minor faulting.
12. Later history not recorded.

BROKEN HILL, NEW SOUTH WALES,
AUSTRALIA,
March 3, 1937.

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GEOLOGY OF THE LITTLE LONG LAC MINE[1]

E. L. BRUCE AND W. SAMUEL.

ABSTRACT.

The Little Long Lac Gold Mine, situated seventy miles north of Lake Superior, is in a broad synclinal belt of greywacke, slates, conglomerates and iron formation that extends from Long Lac westward to Lake Nipigon. The sediments are unconformably above a great series of lavas, and both are intruded by igneous rocks of various ages and types. At Little Long Lac mine the sediments are involved in a great westerly pitching drag fold on the northern limb of the syncline. Subsequent to the folding, east-west zones of shearing developed. Where these cross massive arkosic beds they formed means of easy access for gold-bearing solutions. The ore bodies are confined to the arkosic beds, and ore does not occur in the more schistose material where the major shear zones enter overlying and underlying greywacke.

The ore deposits are lodes made up of narrow veins of quartz along the shear planes. Metallic minerals of some variety are present but are not abundant in the veins. Arsenopyrite and pyrite form about 1½ per cent. of the ore. Gold occurs rather abundantly and uniformly distributed through the quartz so that 20 per cent. of quartz is sufficient to form ore. The wall rocks are little altered and contain little gold.

INTRODUCTION.

The Little Long Lac Mine is on the south side of Barton Bay the western extremity of Little Long Lake, fifty miles east of Lake Nipigon and approximately seventy miles north of Lake Superior. The area in which it is situated lies just north of the height of land between Lake Superior and James Bay. None of the main canoe routes to the north and west cross it and hence little was known about it until the search for iron ores in the early part of the twentieth century led to the prospecting of the iron formations both east and west of Lake Nipigon. Claims were staked at that time covering the ground now occupied by the Little

[1] Published with the permission of the Provincial Geologist, Ont. Dept. of Mines and of the president of the Little Long Lac Gold Mines.

Long Lac mine. Some trenching and stripping was done on the large island west of the mine, but the iron content of the iron formation was found too low to be of any value. No doubt the heavy overburden and extensive low ground discouraged the search on the mainland.

The building of the railway from Long Lac to Port Arthur supplied easy access to the region. Geological maps and reports covering the country adjacent to the railway were prepared both by the Geological Survey of Canada and by the Ontario Bureau of Mines. Parts of the region seemed favorable for the occurrence of mineral deposits.

Assays of a few dollars per ton in gold were obtained from samples taken by A. G. Burrows in 1916 from veins near Jellicoe, 30 miles west of Little Long Lac.[2]

The occurrence of gold in float along the shore south of the main narrows of Little Long Lake is mentioned by Tanton[3] in his report for the field season of 1917.

Claims were staked in that locality but apparently nothing of importance was found in place and interest in the area subsided until the discovery in 1931, of gold in a vein on the shore southeast of the west narrows, at a point where the No. 1 shaft of the Hard Rock Gold mines now is. Much work was done on a mass of porphyry outcropping on the claims staked at the time of that discovery, but results were not considered promising. Hence, although only two miles from the railway, the veins at the Little Long Lac mine were not discovered until mid summer, 1932. Much of the country surrounding Little Long Lake is low and covered with glacial or swamp deposits. Rock outcrops at only a few places along the shores of the lake, and it is not surprising that the gold in the inconspicuous shear zone in which the ore bodies of the Little Long Lac mine occur, remained unrecognized, even though the claim on which it outcrops had been staked for iron in 1907 and, presumably, received some examination at that

[2] Burrows, A. G.: Longuelac to Jellicoe and Orient Bay. Ont. Bur. Mines, vol. 26, 1917.

[3] Tanton, T. L.: The Canadian Northern Railway between Nipigon and Longuelac. Can. Geol. Surv., Summary Rept., pt. E, p. 4, 1917.

time. The occurrence of small quartz veins in shear zones is recorded by Coleman [4] in his report dealing with the iron formations.

GENERAL GEOLOGY.

The general geological relations are fairly simple. A closely folded syncline of sediments lies in lavas mainly of basic character. Both series are intruded by diorite, feldspar porphyry and diabase. Glacial deposits of considerable extent, and in places of unusual depth, overlie the consolidated rocks.

The following table summarizes these relations:

Table of Formations.

Recent and Glacial—Sand, gravel, peat	
Unconformity	
Post Timiskamian—Diabase	
Intrusive contact	
Feldspar porphyry	
Intrusive contact	
Diorite	
Intrusive contact	
Timiskamian	—Conglomerate, greywacke, arkose iron formation
Unconformity	
Keewatin	—Basic lavas, tuffs, iron formation

The Keewatin rocks lie a short distance north of the Little Long Lac mine. They form the basement upon which the sediments were deposited, but as the dip of the formations is steep, and the veins nearly vertical, there is little liklihood that any of the ore bodies at present known will pass downward across the contact.

The rocks assigned to the Timiskaming, consist mainly of greywackes: conglomerate occurs as thin discontinuous beds:

[4] Coleman, A. P.: Iron Ranges of Nipigon Dist. Ont. Bur. Mines, vol. 18, pt. I, p. 146, 1909.

iron formation forms two fairly continuous but lenticular bands in the lower part of the sedimentary series.

Diorite outcrops 600 feet south of the main ore zone. A mass of feldspar porphyry with phenocrysts of acid albite outcrops at the MacLeod Cockshutt Mine a mile and three quarters southeast of Little Long Lac mine. A similar body at least 3400 feet in length with a maximum width of 660 feet has been found in drilling beneath the marshy southwestern extension of Barton Bay, on one of the claims of the Elmos Gold Mines, a mile and three quarters south 65° W. from Little Long Lac Mine. Narrow diabase dikes with northerly trends cut all other rocks.

The thickness of the various members in the Timiskaming Series varies considerably. Especially where the beds are involved in drag folds, some of the rocks, such as iron formation, have suffered considerable thickening at the axes of the folds. Information concerning the stratigraphy has been gained largely by tracing the bands of iron formation by magnetic surveys. Since attractions would occur over a much wider zone along the axes of plunging folds than along the flanks of the folds where the beds are steep or vertical, the apparent thickening of the beds of iron formation at the axes may be less than the magnetic attraction indicates. There is, however, considerable thickening and thinning of the beds due to deformation. Near the ore zone, drilling has made possible more accurate estimates of the thickness of various members of the series, but the variation in character of sediments, apparently in the same bed, makes the placing of contacts somewhat uncertain. Thicknesses as indicated by magnetic surveys and by diamond drilling are shown below for two sections, one east of the folded area approximately 5000 feet east of the shaft, the other west of the folded area approximately 600 feet west of the shaft.

The beds shown at the top of the sections are at the north and are the oldest. The direction of the sections is S. 20° W., which is thought to be approximately normal to the average strike. This is by no means the complete sedimentary series, which must be very thick, but only the lower part.

Section 600′ west of shaft	*Section 5000′ east of shaft*
	0–120 flows
0–220 iron formation	120–700 iron formation
220–400 unknown	700–1000 arkose
	1000–1400 greywacke
400–1000 arkose, probably the Little Long Lac band	1400–2050 arkose, probably the Little Long Lac band
1000– ? greywacke	2050–2300 greywacke
?	2300–2900 Interbedded greywacke and coarser fragmental
1300–1450 iron formation	2900–4000 iron formation

The minerals of the rocks of most of the beds of the series are the same but they are present in different proportions. The rock classed as arkose is scarcely typical arkose as it contains approximately 40 per cent quartz and less than 30 per cent feldspar. Sericite makes up a considerable part. There is some carbonate and sufficient chlorite to account for the grey color. The greywackes are mostly somewhat finer grained and are darker in color as they contain a greater proportion of chlorite. The iron formations are those zones where bands or lenses of hematite and magnetite become abundant in the greywacke or where laminae high in iron oxide are interlayered with quartz or jasper. Bands of iron formation in which the iron content is as much as 30 per cent, grade into ordinary greywacke with only a few thin lenses of magnetite and hematite. The boundary between rocks called iron formation and those classed as greywacke is thus largely an arbitrary one.

The arkose or feldspathic quartzite in which the veins at the Little Long Lac mine occur, is massive and so uniform that bedding can be detected at only a few places in it. It is greyish in color with vitreous lustre. Under the microscope it is found to have quartz as its most abundant constituent. Plagioclase feldspar, most of which is acid albite in composition is next in abundance. The other constituents are carbonates, chlorite, and sericite. The feldspar is quite fresh, evidently formed by recrystallization and not residual. Both it and the quartz are fractured and in places sheared into lenticles.

The rock below the arkose is finer grained, darker in color and softer. It contains a larger proportion of chlorite than the upper bed, but considerable quartz and feldspar are present.

Immediately above the arkose there is an irregular bed 8 to 48 inches thick in which the fragments are larger than those of the arkose. Above this bed, the rock is massive greywacke very similar to that below the arkose.

The sediments lie in a great syncline the northern edge of which is 2,800 feet north of the shaft of the Little Long Lac mine. The axis of the syncline lies an unknown distance to the south.

Near the mine, the major structure is complicated by a large drag fold. In following beds from the east westward they are found to be bent back on themselves and carried northward about three thousand feet before resuming their regular westward trend. The intersection of the bedding with the main shear zone at the contact of the arkose and greywacke in the mine workings, shows that the drag fold plunges to the west at an angle of approximately 50 degrees. The axial plane of the anticlinal part of the drag fold is slightly curved. To the east of the mine its strike is about N. 88° E., to the west it is N. 80° E. Subsequent to the folding, zones of shearing developed, which are approximately parallel to the axial plane of the fold (Fig. 1). The major joint planes are horizontal and probably were formed contemporaneously with the shear zones.

THE ORE DEPOSIT.

The ore bodies of the Little Long Lac mine are lodes composed of narrow quartz veins sufficiently closely spaced to make possible the mining of the intervening rock in which the gold content is low. The main lode lies about 80 feet south of the anticlinal axis of the drag fold. Its general strike is N. 80° E., but in parts it varies slightly from that direction. The dip is steep to the south.

Ore bodies have been found only in the massive arkose. Apparently in that rock definite shear planes were formed, whereas the finer grained greywacke, both above and below, was less brittle and movements developed in it a schistosity that offered fewer or

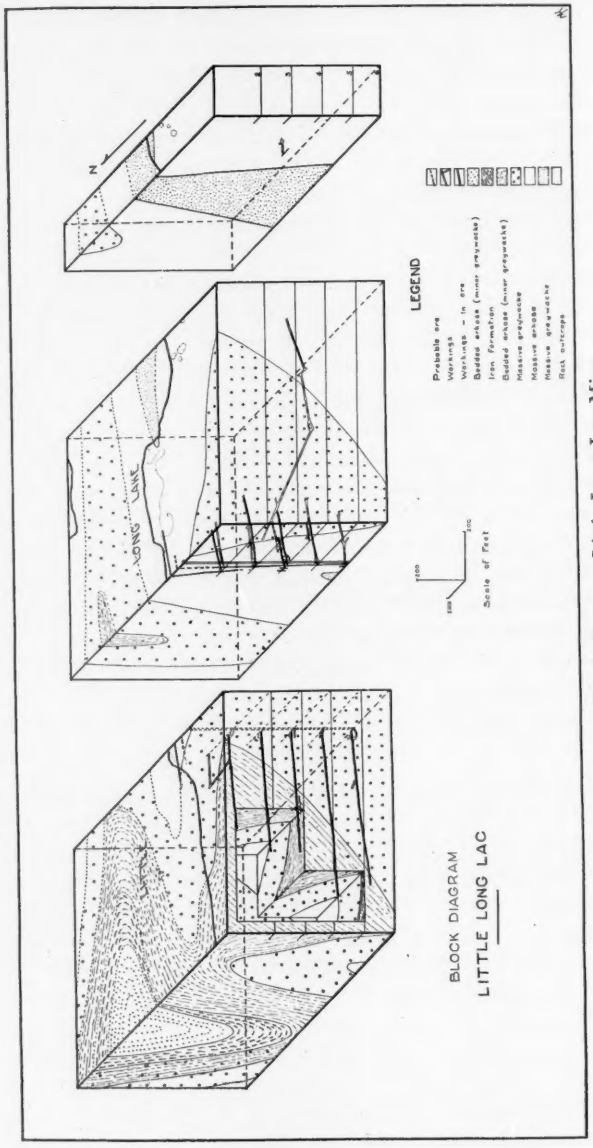

FIG. 1. Block diagram, Little Long Lac Mine.

smaller and less continuous openings for the vein forming solutions.

The quartz veins vary from mere cracks up to widths of six or eight inches. Commonly one or more major veins have narrow parallel veins between them and there are also oblique veins connecting the parallel ones. In general, even the narrowest veinlets have a remarkable persistence and some only a fraction of an inch in width can be traced without interruption for several feet (Fig. 3).

All the veins are lenticular, however, and any one followed far enough along its strike will be found to taper out. Where one ends, other veins commonly begin along parallel shear planes. Thus the total amount of quartz in any cross section of a vein zone in the arkose is approximately constant. In places there are transverse veinlets containing calcite. Some quartz veins abuting horizontal veinlets of this kind, are offset as if faulted. In all cases yet noted the quartz replaces the calcite in the transverse vein and the offset is due to the fact that the shear plane was faulted before the vein material came in; the solutions simply travelled along the offsetting fissure to a point where the displaced shear plane could again be entered.

During early development it was considered that there was a single lode. Other parallel lodes have now been found. As yet they have not been shown to be as regular or as continuous as the main one, but it seems possible that the one mentioned below, north of the shaft on the 2nd level, may actually be the one that outcrops on the surface and that the main lode, on which the major part of the work below the 2nd level has been done, does not outcrop (Fig. 1).

At a point 30 feet east of the shaft on the second level (*a*, Fig. 2) two six inch quartz veins and a number of parallel veinlets diverge from the main vein zone, curve to the north, back to the west and then back in a reverse curve; the most northerly form a zone parallel to the main zone and 50 feet to the north of it. These curved veins thus have the form of a complete drag fold, the axis of which plunges to the east at an angle of 48 de-

FIG. 1. Block diagram, Little Long Lac Mine.

grees. The strike of the axial plane of the anticlinal part of the fold is east-west and its dip approximately 70 degrees to the north. Above the second level and for sixty feet below it, an ore shoot with a stope length of 60 feet and a width of 40 feet has been opened up along the thickened crest and trough of the fold.

In addition to this complete drag fold there are two others (*b* and *c*, Fig. 2) in which some quartz veins and veinlets diverge

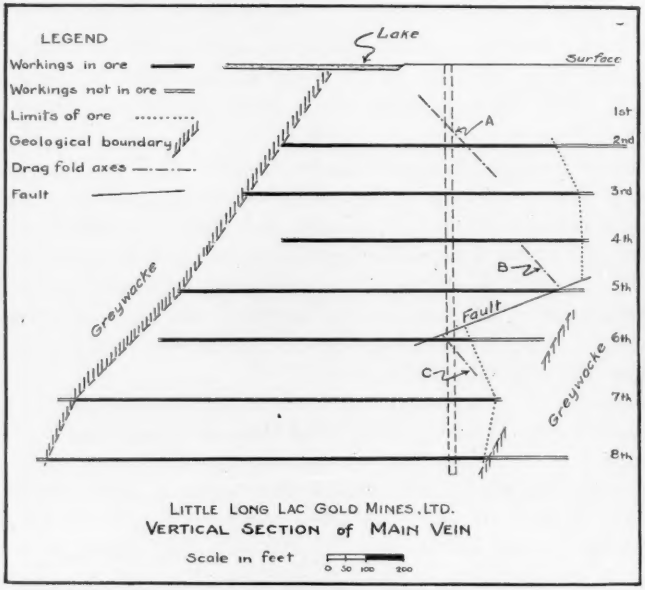

FIG. 2. Longitudinal section through the workings, Little Long Lac Mine.

from the main vein zone and form the anticlinal part of a drag fold (Fig. 4); but the quartz in these folds narrows so that the material is below ore grade where the synclinal portion of the fold should be.

In stoping between the third and second levels it was found

that the curved linking veins (*a*, Fig. 2) became narrow downward from a point fifty feet above the third level, that the main vein zone and the north vein zone persist, but with no evidence of linking on the third or fourth levels. The vein with a partial drag folded form found on the fifth level (*b*, Fig. 2) may possibly be the downward continuation of that shown at "*a*" on the second level, the apparent displacement being due to slight changes in the dips of the axial planes of the fold or a change in dip of the main vein zone.

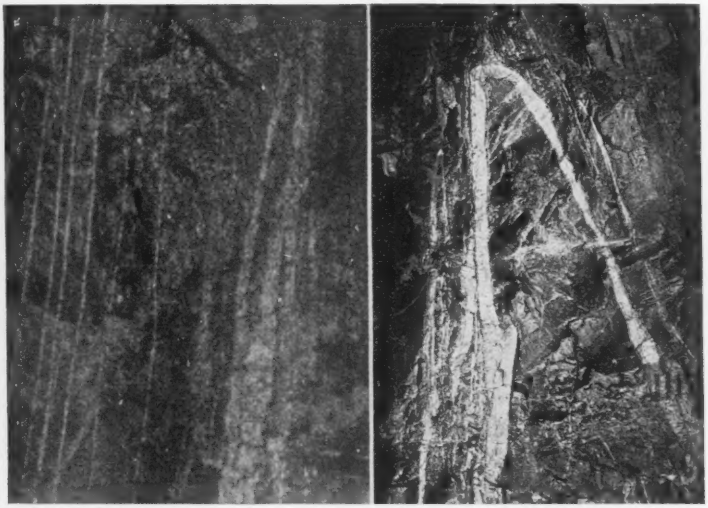

FIG. 3 (Left). Back of second level west of the shaft, Little Long Lac Mine. Area shown 4½′ × 6′. Ont. Dept. of Mines Ann. Rept., vol. 44, pt. 3.

FIG. 4. Anticlinal part of linking vein in station 6th level (700′), Little Long Lac Mine. Area shown 8 feet × 5 feet.

It is evident that although the ore bodies are mainly in the parallel east-west shear zones, these curved linking veins must follow structures so obscure that they have not yet been recognized. It seems most likely that they are bedding planes. The

westward plunging drag folds in the sedimentary series are no doubt related to the folding of the syncline. They were formed by the movement of southern beds upward relatively to those north of the drag folded zone. Assuming that the pitch was imposed on the folds when the syncline was formed, the relative upward movement must have been in a direction inclined 50° west from the vertical. On the other hand, the drag folded form shown by the linking veins indicates a movement of the south side upward with reference to the north, but in a direction at 50° east from the vertical. On the 8th level, however, a band of conglomerate occurs near the western contact between greywacke and arkose. It is not displaced in an east-west direction by the vein shear zone. Hence the movement along the shear must have been in a direction parallel to the contact between the two beds, upward at an angle of 40° east from the vertical. In that case the plunge of the drag folded linking veins should be 40 degrees to the east (Fig. 5). It seems quite possible that local changes in the directions of stresses might result in slight local variations.

Although the south side moved up relatively to the north side both during the formation of the westward pitching drag folds in the sedimentary beds and during the buckling of some obscure structure into the easterly pitching linking veins, the direction of movement in the latter case was at 90 degrees from the former.

Faults subsequent to the formation of the veins have not disturbed them to any great extent in a north south direction. A low angle fault encountered on the 2nd level strikes N. 75° E. and dips 15° south. It should come to the surface under the lake. In places, along the second level, it is an open fissure from which a large quantity of water entered the workings until the openings were sealed off with cement.[5] At other places the sides of the fault are so closely pressed together that it is hardly discernible. The movement along this plane has disturbed the vein only slightly. The upper side shows a displacement to the north of only a few inches. The shaft passed through a low angle fault at 275 feet. Other similar faults have been intersected

[5] Barton, A. A.: Cementation. Can. Mining Jour., No. 12, pp. 529–530, 1934.

during mining operations, but none of them has displaced the vein more than a few feet.

A fault on the fifth and sixth levels (Fig. 2) displaces the part of the vein above and to the west of the fault ten feet to the north. There may also have been a movement of the upper part upward and to the east parallel to the vein, as vein material has been found above the fault along the fifth level and above the fifth level

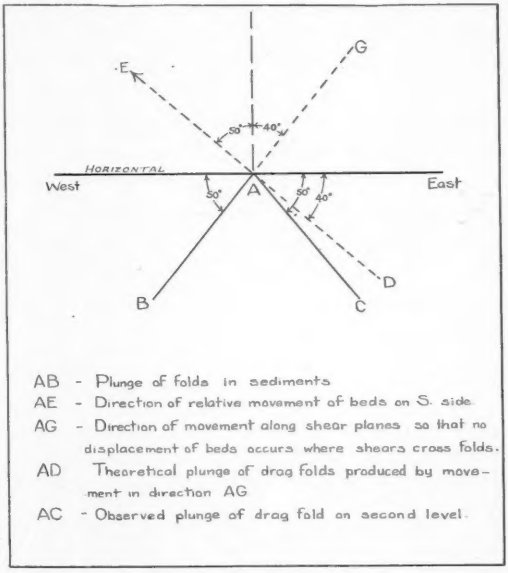

FIG. 5. Diagram showing relation of fold axis to directions of relative movement.

but cross cuts from the fifth level east of the fault show no ore. It is possible that such an east-west component to the fault movement may explain the fact that the partial drag fold that occurs in the station on the 700 foot level (*c*, Fig. 2) is not found above the fault in the stope immediately west of the shaft. If the upper

side were thrust up along the fault plane a distance of 250 feet the upward continuation of the drag fold shown at "*c*" (Fig. 2) would have the position of that shown at "*b*."

The vein filling consists mostly of fine grained white quartz in which only small quantities of other minerals are found. The quartz is of two periods, an older fractured variety and a younger clear, finer grained variety which occurs as veinlets cutting the older type. The metallic minerals occur in the older quartz. They are most abundant along dark streaks but are also in white, apparently unfractured quartz. Those reported are arsenopyrite, pyrite, stibnite, pyrrhotite, tetrahedrite, bournonite, berthierite, chalcopyrite, galena, hematite, sphalerite and magnetite.

Pyrite is the most abundant metallic mineral in the ore. Analyses of the mill heads by the Mines Branch Laboratory, Ottawa,[6] show a content of 0.30 per cent As, 0.60 per cent S, 0.01 per cent Sb, 0.02 per cent Bi, 0.02 per cent Zn, 0.01 per cent Cu, and 0.02 per cent Pb. These quantities correspond to a content of 0.84 per cent pyrite and 0.65 per cent arsenopyrite when the other metals are assumed to be present as simple sulphides. Pyrite is commonly in isolated, fairly well formed, cubes or irregular grains. In places, commonly along fractures, there are aggregates of grains or crystals. Arsenopyrite is generally in well formed elongated crystals less than 1/16 of an inch in length. They occur singly or in aggregates with pyrite. Many of the crystals and grains, both of pyrite and arsenopyrite, are fractured. Bournonite (Fig. 6) is present in some specimens, forming a cement for fractured pyrite. Stibnite is found in segregations half an inch in diameter but does not seem to occur with the other metallic constituents of the ore. Thomson[7] has reported the presence in specimens examined of tetrahedrite, berthierite and chalcopyrite, all of which are rare. He describes berthierite ($FeS\ Sb_2\ S_3$) as in needle like crystals aggregated along tiny cracks. Tetrahedrite is described as tiny blebs and veins in arsenopyrite,

[6] Ont. Dept. Mines, Ann. Rept., vol. 44, pt. 3, p. 40, 1935.

[7] Thomson, Ellis: Contributions to Canadian Mineralogy. Univ. of Toronto Studies, 1935, pp. 37–45.

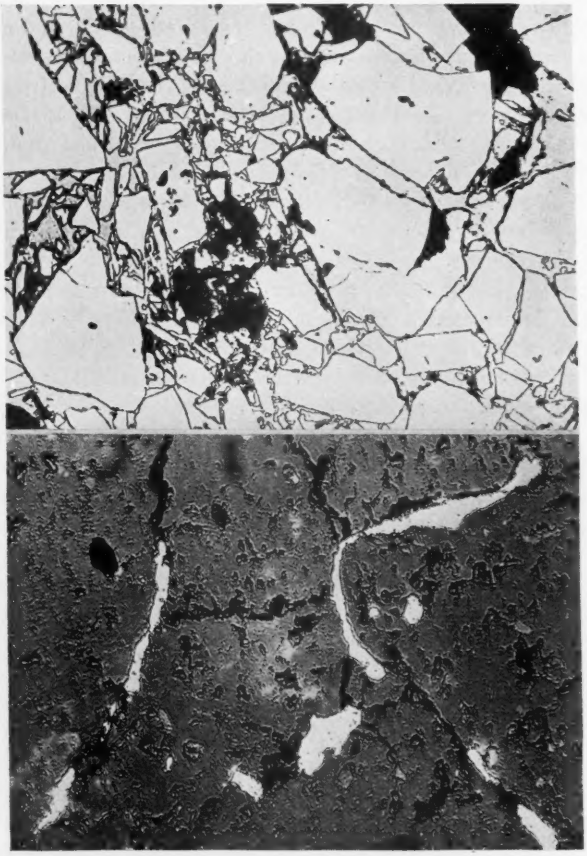

FIG. 6. Photomicrograph of Little Long Lac ore. Fractured pyrite (white) cemented by bournonite (gray) × 200. Ont. Dept. of Mines Ann. Rept., vol. 44, pt. 3.

FIG. 7. Photomicrograph of Little Long Lac ore. Gold (white) filling fractures in quartz. × 200. Ont. Dept. of Mines Ann. Rept., vol. 44, pt. 3.

pyrrhotite, or the gangue. Only very small amounts of metallic minerals other than pyrite and arsenopyrite are present and many specimens, therefore, contain none or few of these rarer species.

Gold is distributed in visible quantities in the quartz of the ore zones. It occurs both along sericitic slip planes and in massive quartz. Much of it is in fine particles and the regularity of the distribution is remarkable. The quartz contains the greater part of the gold present in the vein zone. The wall rocks contain little. Twenty per cent of quartz is quite sufficient to form ore of the present mill grade.

Gold occurs as veinlets in quartz (Fig. 7) as tiny blebs in apparently unfractured quartz, as thin plates along the faces of pyrite and arsenopyrite crystals, in fractures in them and as blebs within crystals that show no fractures. Tiny rounded grains are present even within the bournonite. Evidently the period of gold deposition was a long one and may have overlapped that of several of the other minerals. As no single specimen contains all of the minerals reported to occur, and even where present, the grains are commonly isolated, it is impossible to give a complete statement of the order of deposition. Thomson [8] gives the following order for the minerals of the Little Long Lac and other mines of that area—

1. Quartz, pyrite, arsenopyrite, magnetite.
2. Quartz, pyrite, arsenopyrite, pyrrhotite, chalcopyrite, sphalerite and carbonate.
3. Carbonate, pyrite, berthierite, sphalerite.
4. Galena, gold, tetrahedrite.
5. Limonite.

A somewhat different order was suggested [9] for the major metallic constituents as follows—

1. Calcite, quartz.
2. Arsenopyrite, pyrite, bournonite and gold forming an overlapping sequence in which some gold was deposited before arsenopyrite had completed its period of crystallization.

[8] Thomson, Ellis: *Op. cit.*, p. 42.

[9] Bruce, E. L.: Little Long Lac gold area. Ont. Dept. Mines, vol. 44, pt. 3, p. 42.

3. A second generation of quartz which began somewhat before the completion of the crystallization of pyrite and which continued after all other minerals had formed.

Origin.

It has been shown that during the movement along the shear planes in which the veins occur, the south side moved upward and to the east whereas during the folding of the sediments the movement of the south side must have been upward and to the west. The two directions of movement were at 90 degrees to each other since the shearing did not offset the bedding of the sediments. No evidence is available as to the cause of the movement upward and easterly. It may be significant, however, that the porphyry bodies, with which the ore bodies of the MacLeod Cockshutt mine 1¾ miles to the southeast are associated, are pipe like masses with a rake to the west following the direction of plunge of the folds. In some way they must have been forced eastward up along the axes of the folds, and it is conceivable that the stresses resulting in its intrusion may have been responsible for some of the shearing in the sediments. If so, movements must have continued after the emplacement of the porphyry, since it also is sheared and fractured. Neither the origin of the stresses that produced the shear zones at the Little Long Lac Mine, nor the period during which they were formed, can, therefore, be definitely determined. The shearing is older than the diabase dikes which cut across the vein zones without any apparent displacement.

The solutions from which the vein minerals were deposited were siliceous through the greater part of the period of mineralization. That period was one of considerable length and probably some complexity, since the quartz is of two generations at least. Furthermore, the minerals present indicate a considerable range in temperature, from the fairly elevated temperature of which pyrrhotite and arsenopyrite are characteristic, to the moderate ones that must be supposed to have obtained during the deposition of bournonite, stibnite and similar minerals.

The mass of porphyry outcropping at the MacLeod Cockshutt mine and the unexposed body southwest of Little Long Lac mine are the only intrusives in the vicinity of the Little Long Lac ore bodies of such character that they could be genetically related to the vein material. As gold-bearing quartz veins occur in sheared and fractured zones in some of the porphyry bodies it seems doubtful that there can be any direct relationship between the porphyry and the ore solutions. It seems likely that the intrusive rocks derived from the magma from which the ore solutions came are still unexposed.

QUEENS UNIVERSITY,
KINGSTON, ONT.,
March 10, 1937.

MINERALIZATION AND METAMORPHISM AT THE EUSTIS MINE, QUEBEC.[1]

JOHN S. STEVENSON.

ABSTRACT.

The unique pyrite-chalcopyrite deposit of the Eustis mine is described in detail. Attention is directed to its association with sodic rocks and to the localization of pyrrhotite and cubanite in the ore.

The country rocks comprise schistose sodic porphyry, muscovite schist that has resulted from the metamorphism of the porphyry, and "green rock," a massive carbonate rock that is largely a hydrothermal alteration product of the schist. A study of the chemical analyses of these genetically related rock types is presented.

The ore bodies consist of four large pyrite-chalcopyrite lenses arranged *en echelon* and extending down the dip of the enclosing schist for 6,500 feet to the present (1935) depth of mining. High temperature minerals, including anthophyllite and exsolved pyrrhotite and cubanite, have been localized where the chalcopyrite ore-body has been metamorphosed by the intrusion of a 40-foot camptonite dike.

The source of the ore solutions is not definitely known, but it is thought that they came, not directly from the porphyry, but from a common magma, a magma characterized by the ability to yield sodic rocks and associated pyritic ore-bodies.

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[1] Adapted from the author's thesis in partial fulfillment of the requirements for the degree of Doctor of Philosophy, in the Department of Geology, the Massachusetts Institute of Technology, 1934.

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INTRODUCTION.

It is the purpose of this paper to describe the unique mineralization of the Eustis Mine, which has resulted in the development of a lens of continuous chalcopyrite-pyrite ore that has been worked for over 6,500 feet down the dip; and has caused important changes in the immediate country rock. In addition, the composition of the ore lenses has been changed locally by the heat accompanying the intrusion of a lamprophyre (camptonite) dike, the change resulting in a metamorphosed ore body.

The Eustis Mine is situated about 10 miles southeast of Sherbrooke, in the Eastern Townships of Quebec. It is one of the oldest copper mines in Canada, having been more or less continuously operated since 1865. A recent paper by Snow and Brownbill [2] describes mining operations.

The present investigation consisted of an underground study of the mine during the summer of 1933, and of work in the Laboratory of Economic Geology at the Massachusetts Institute of Technology.

[2] Snow, F. W., and Brownbill, H. F.: Mining methods and costs at the Eustis Mine. Can. Inst. Min. Met. Bull. 286, pp. 70–85, Feb., 1936.

GEOLOGICAL SETTING OF THE EUSTIS MINE.[8]

The Eustis ore body lies in schists that constitute one unit in a group of three schist belts that are the northeastward extension of the Appalachian mountain system into Canada. In southeastern Quebec the Appalachian system is represented by a set of three parallel groups of hills trending northeasterly. The most westerly extends northeastward from the vicinity of Lake Champlain, a low intermediate group from near Lake Memphremagog, and an easterly from near Lake Megantic. The Eustis is in the second one. These hills are anticlinical ridges of metamorphic rocks and contain the copper replacement deposits of southeastern Quebec.

The rocks include metamorphic, igneous and sedimentary types and later intrusions of Devonian age. The metamorphosed igneous rocks comprise chlorite schist, schistose quartz porphyry, and muscovite schist.

The chlorite schist has been derived from diabases and fine-grained diorites or andesites; the muscovite schist from quartz porphyries. Metamorphosed sedimentary rocks are not abundant in the Eustis belt. Later intrusives include granite and basic dikes.

Country Rock.

The rock types in the Eustis Mine comprise schistose quartz porphyry (Fig. 1), muscovite schist (Fig. 2), "green rock," and later lamprophyre dikes. The schistose quartz porphyry does not occur closer than approximately 500 feet to the ore bodies, but the muscovite schist and most of the green rock lie adjacent to the ore bodies. The lamprophyre dikes are widespread. The nearest area of known exposed granite is at Barnston, some 12 miles south of the Eustis. Except for the lamprophyre dikes, the rock types are considered to be variations of the quartz porphyry, the textural and mineralogical differences resulting from different intensities of hydrothermal alteration.

[8] Abstracted from, "The Copper Deposits of the Eastern Townships," by J. Austen Bancroft, Quebec Mines Branch, 1915.

Schistose Quartz Porphyry.—The texture of this rock varies; there are definitely porphyritic phases (Fig. 1) that become schistose, and others that become laminated. An analogy to the laminated variety and its origin is indicated by the banded phases of alaskite porphyry from the Shasta county, California, copper deposits described by Graton.[4]

Microscopic study of phases of the Eustis quartz porphyry shows that they contain no glass as might be expected in flow rocks. In general the texture is definitely porphyritic. The phenocrysts are quartz, albite, and an occasional carbonate grain; and in most cases the groundmass consists of fine-grained quartz and feldspar, with coarser-grained muscovite, chlorite, epidote, and titanite. The quartz phenocrysts show undulatory extinction and contain strings of inclusions arranged in sub-parallel rows. The parallelism of these does not conform to the schistosity and there is a suggestion that some have been rotated. It is to be noted, however, that there is no development of mortar structure. The albite phenocrysts, similar in size to the quartz grains, are remarkably free from alteration products. Only a few shreds of sericite occur in each phenocryst. The albite has, however, been more susceptible to internal fracturing than has the quartz, and fractures in many of the albite phenocrysts have been filled by quartz. Where more badly broken than by a single fracture, the ancestry of the various fragments can be traced to one phenocryst, rotation and movement of the fragments being quite discernible. The greater susceptibility of albite, in comparison with quartz, to destruction by comminution and alteration indicates that the albite will, upon the application of greater stresses, disappear first. This feature accounts for the absence of albite in the schist of the ore zone.

Although muscovite is present in all of the rock types, it rarely exceeds one per cent in the quartz porphyry. Epidote, although not common, occurs in amounts not exceeding one per cent. Carbonate has two modes of occurrence, one as discrete well-

[4] Graton, L. C.: The occurrence of copper in Shasta County, California. U. S. Geol. Surv. Bull. 430, p. 84, 1910.

formed rhombohedrons that contain numerous residuals of quartz, and the other as narrow veinlets that cross-cut any schistosity present. The carbonate of these veinlets is thought to be later in age than that which is so abundant in the green rock. Titanite occurs as an occasional constituent.

Chlorite, although not common, is widespread. It has been identified as diabandite, the variety that is common in the green rock. The diabandite possesses a shreddy habit; nowhere is it arranged in aggregates the form of which would imply a derivation from a pre-existing ferro-magnesian mineral. The shreds are commonly concentrated in bands of granular quartz that parallel the schistosity. It is thought that this chlorite is not a recrystallized or alteration product, but rather one that is the result of deposition from hydrothermal solutions.

Although the alterations effected by hydrothermal solutions in the quartz porphyry and its closely allied phases have been slight, they are manifested in the development of quartz in the quartz tails and veinlets, and in the development of carbonate veinlets and diabandite chlorite.

Muscovite Schist.—This schist occurs in the ore zone. It is much more schistose, sheared, and contorted than that found elsewhere (Fig. 2). Contact relationships between the schist and both the green rock and the ore indicate that it has been replaced by both. The minerals composing it are: muscovite, quartz, chlorite, carbonate, quartz-albite veinlets, and disseminated pyrite.

Muscovite, in amounts varying from 5 to 75 per cent., occurs as isolated laths, as curving foils of shreddy muscovite, and as fracture fillings in residual quartz phenocrysts (Fig. 2).

Quartz forms about 10 per cent. of the rock in the muscovite varieties, and about 75 per cent. in the quartzose varieties. The latter, however, are uncommon. Three distinct types of quartz occur. One, fine-grained, forms a groundmass for the other common minerals, and represents recrystallized quartz of the much finer-grained groundmass in the quartz porphyry outside the ore zone. A second, medium-grained type occurs in lenticular

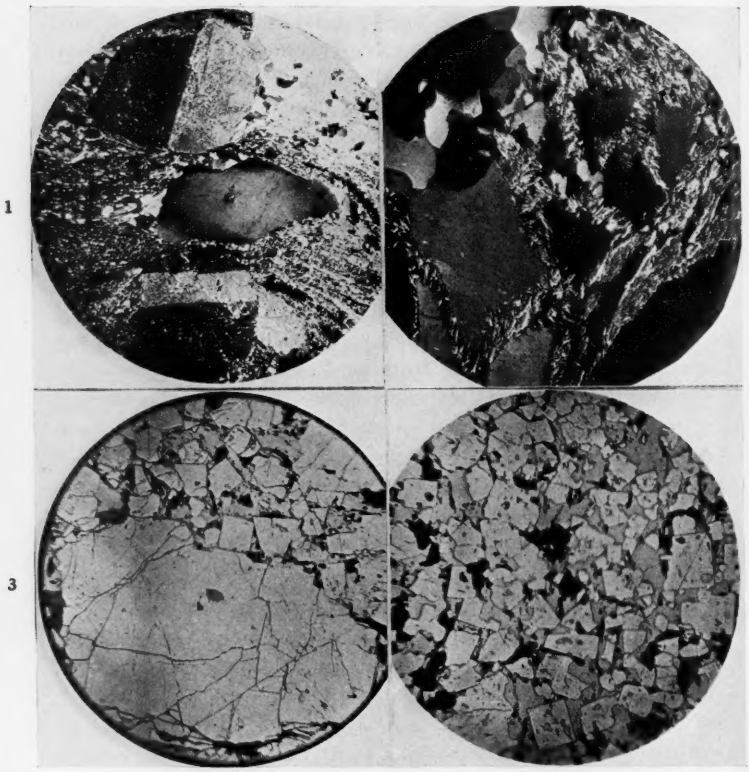

FIG. 1. Schistose quartz porphyry. ×-nicols. × 55.

FIG. 2. Muscovite schist of ore zone, with broken quartz phenocrysts and muscovite. ×-nicols. × 55.

FIG. 3. Porphyritic ore; large phenocryst of pyrite in lower half, cubic pyrite and chalcopyrite (darker grey) in upper half. × 19.

FIG. 4. Cubical pyrite. Note perfect pyrite cubes (light grey) except where embayed by replacing chalcopyrite (darker grey). × 19.

areas as a mosaic of clear quartz grains, as feather quartz around pyrite cubes, and as a constituent of the late quartz-albite veinlets. The albite of these veinlets is quite clear and free from sericitic alteration. A third type is represented by quartz phenocrysts. These occur in the muscovite schist of the ore zone, although they are much more abundant in the porphyry outside of the ore zone. The phenocrysts are of the same general size but differ in that those of the muscovite schist are more generally fractured and dismembered (Fig. 2). The presence of these quartz phenocrysts serves to identify the schist of the ore zone as a highly altered phase of the adjacent porphyry.

A chlorite, amesite, is developed in varying amounts throughout the muscovite schists. In places there is only about one per cent. present, and the average is less than 5 per cent., but in some highly sheared rocks this mineral and sulphides are the only constituents. The amesite occurs as small single laths and as large, fan-shaped bundles of such laths. The boundaries of these are everywhere clean and sharp. They show no sign of alteration, either centrally or peripherally, as is so common with chlorites that are formed from pre-existing ferro-magnesian minerals. The amesite is considered to be a late mineral, originating as a result partly of hydrothermal action and partly of recrystallization. It formed in the schist previous to the sulphides and before the last introduction of quartz. In the green rock, where amesite is rarely present, it formed after the main development of carbonate.

Isolated grains of carbonate occur in the muscovite schist. These are clear-grained, lacking the cloudiness and the numerous rutile needles of the carbonate in the green rock. The carbonate of the schist does, however, contain many rounded quartz inclusions; these are relicts of the groundmass. This carbonate is considered to be of late development.

Numerous late veinlets traverse the rock in the ore zone. These comprise quartz-albite-carbonate, quartz-albite-carbonate-chlorite, and quartz-sulphide veinlets. The chlorite found in these is a variety identified as prochlorite.

Green Rock.—Green rock is the name applied to a distinctly green, massive rock that occurs as large blocks and as sills in the schist of the ore zone. Blocks of green rock range in size from 75 feet in diameter to small remnants in the ore which are hardly recognizable. The sills range in width from 3 feet to half an inch. Although a few green rock blocks have been seen as much as 800 feet from the ore body, the sills appear to occur only in the immediate vicinity of the ore. Oxidation yields a rusty product because of its high iron content; fresh faces are, however, greenish, varying from a dull green to a light buff.

The most outstanding feature of the green rock is its massive structure. The enclosing schist is always schistose but the green rock is blocky, possessing an almost conchoidal fracture. This large-scale massiveness is a feature strikingly similar to that of the ore body. The resemblance genetically relates the two: that is, both have been formed by replacement of a schist.

The texture of the green rock is granular and, in many cases, imperfectly schistose. The schistosity, where discernible, is always parallel to that of the enclosing schist, and is probably an inheritance from the schist, which it is thought to replace. In a few instances definite residuals of schist in the green rock were seen. These are small and close to the border of the green rock block. The residuals form lenticular areas from 2 to 4 inches long and from 1 inch to a sixteenth of an inch wide, and grade imperceptibly into the surrounding green rock. The imperfect schistosity or banding of the green rock conforms also to the banding of the ore. The immediate contact of the green rock and the ore is less sharp than that of the green rock and the schist. These contacts have been definitely corroded by the ore, and cross-cutting veinlets of sulphides occur through the green rock.

Under the microscope the texture is seen to range from even-granular to slightly schistose.

Listed in order of abundance, the minerals found in the green rock are as follows:

	Per Cent.	
	Blocky Masses	Sills
Quartz	58	37
Carbonate	25	50
Muscovite	10	10
Chlorite	6	2
Rutile and leucoxene	1	1

Anhedral grains of quartz form the groundmass; numerous grains also occur as inclusions in the carbonate grains.

The carbonate of the green rock is ankerite, which lacks good crystal outlines; this is in marked contrast to the almost perfect development of the vein calcite. Another characteristic is the large number and variety of minerals found as inclusions in it. These, in order of abundance, are: quartz, muscovite, and rutile; chlorite is noticeably absent. Quartz inclusions may amount to 50 per cent. of a carbonate grain.

Muscovite, although common in the green rock, is distributed at random, both as laths and as broad low doubly-refracting plates. The predominate chlorite in the green rock is diabandite. Some of it is segregated into narrow bands, and a smaller amount occurs as disseminated laths throughout the rock. In addition to diabandite, amesite chlorite is present in small amounts as isolated bunches of laths.

Rutile and its alteration product, leucoxene, are abundant in the green rock, and the amount varies directly with the amount of carbonate; they are absent in the schists. These features indicate that the rutile as well as the ankerite is an introduced hydrothermal mineral.

Lamprophyre Dikes.—The country rocks and sulphide lenses of the Eustis have been cut by numerous lamprophyre dikes which vary greatly in composition and width. Olivine diabase, camptonite, and monchiquite dikes have been recognized. The thickness of these ranges from mere stringers of a sixteenth of an inch or less, to one, a large camptonite dike on the 4,850-foot level, which is 40 feet wide.

Chemical Features of Wall Rock Alteration.—The chemical features of the three rock types, quartz porphyry, muscovite schist, and green rock, are shown in the accompanying tables.

Table 1 illustrates the changes involved in the development of the muscovite schist from the quartz porphyry on the basis of no appreciable change in volume. Column I represents the quartz porphyry, and II the schist; III represents the composition of the same volume of schist in percentage of the original quartz porphyry mass; the figures in this column are a more accurate representation of the changes involved. There has been a considerable addition of magnesium and potassium and an increase in ferric iron. Slight amounts of silica and ferrous iron were also added. The losses include aluminum, titanium, and a comparatively large amount of soda.

TABLE 1.

ALTERATION OF COUNTRY ROCK AND ABSOLUTE GAINS AND LOSSES PER CUBIC METER. EUSTIS MINE, QUE.

(Analyst, A. Willman.)

	I	II	III	IV	V
SiO_2	78.71	76.45	78.8	2127.4	2131.4
Al_2O_3	11.22	8.03	8.28	303.2	223.8
Fe_2O_3	0.74	4.61	4.76	20.0	128.6
FeO	1.21	1.59	1.64	32.7	44.3
MgO	0.77	1.58	1.63	20.8	44.0
CaO	0.95	None	None	25.6	
Na_2O	4.35	0.26	0.27	117.5	7.2
K_2O	0.82	1.70	1.75	22.1	47.3
H_2O	Not det.	Not det.		Not det.	Not det.
TiO_2	0.25	0.09	0.092	6.7	2.5
Total	99.02	94.31	97.22	2676.0	2629.1
Sp. Gr.	2.703	2.788			
Net Loss					46.9

I. Quartz porphyry, 2,800-foot level, 800 feet east from shaft.
II. Muscovite schist, 5,300-foot level.
III. Composition of the same volume of schist in percentage of original quartz porphyry mass.
IV. Kilograms per cubic meter of quartz porphyry.
V. Kilograms per cubic meter of muscovite schist.

Columns IV and V represent the absolute gains and losses per cubic meter. Such figures were obtained by multiplying the percentages of I and II by 2.703 and 2.788 respectively, the specific gravities of the quartz porphyry and the muscovite schist. The calculation shows that, during the alteration of

quartz porphyry to schist, 172 kilograms were added and 219 lost per cubic meter, the net loss being 47 kilograms per meter.

The chemical changes between the schist and the green rock are much more intense than those between the porphyry and schist. Table 2 illustrates these as in Table 1, on the basis of no volume change. Column I represents the composition of the schist, II the green rock, and III the composition of the green rock in terms of the original mass of schist. These figures show that there has been a considerable addition of aluminum, ferrous iron, mag-

TABLE 2.

ALTERATION OF COUNTRY ROCK AND ABSOLUTE GAINS AND LOSSES PER CUBIC METER. EUSTIS MINE, QUE.

(Analyst, A. Willman.)

	I	II	III	IV	V
SiO_2	76.45	48.44	49.1	2131.4	1369.9
Al_2O_3	8.03	13.34	13.51	223.8	377.2
Fe_2O_3	4.61	0.40	0.41	128.6	11.3
FeO	1.59	7.31	7.41	44.3	206.7
MgO	1.58	5.16	5.24	44.0	145.9
CaO		8.50	8.63		240.3
Na_2O	0.26	1.68	1.70	7.2	47.5
K_2O	1.70	0.22	0.22	47.3	6.2
CO_2		9.72	9.85		274.8
H_2O	Not det.	Not det.		Not det.	Not det.
TiO_2	0.09	1.39	1.41	2.5	39.3
Total	94.31	96.16	97.48	2629.1	2719.1
Sp. Gr.	2.788	2.828			
Net Gain					90.0

I. Muscovite schist, 5,300-foot level.
II. Green rock, Slide Drift near shaft.
III. Composition of the same volume of green rock in percentage of muscovite schist.
IV. Kilograms per cubic meter of muscovite schist.
V. Kilograms per cubic meter of green rock.

nesium, calcium, titanium, and carbon dioxide; to a lesser degree, of sodium. There has been a comparatively large loss of silica, and also minor losses of ferric iron and potassium oxides. The increase in sodium as from schist to green rock may be attributed to a slight development of paragonite mica corresponding to a decrease in potassic mica or muscovite.

Columns IV and V represent the absolute gains and losses per cubic meter. The figures were obtained as before. Such cal-

culations show that, during the alteration of portions of the schist to green rock, 1,009 kilograms were added and 919 lost per cubic meter, the net gain being 90 kilograms per cubic meter.

That the changes involved in the alteration of portions of the schist to green rock have been much more intense than the moderate change from quartz porphyry to schist is exemplified in the relative transfers of material. In the schist-green rock alteration, 1,009 + 919 or 2,020 kilograms per cubic meter were exchanged; but in the quartz porphyry-schist development the interchange amounted to only 172 + 219 or 491 kilograms per cubic meter. The large transfer of material in the formation of green rock from schist, together with the generalization that the green rock occurs close to the ore bodies, indicates that this massive carbonate rock has been formed largely by the effect of hydrothermal solutions on the schists.

The green rock is considered to be the result of mineralization and replacement of the schist. Its large-scale massiveness relates it in general appearance to the undoubted results of hydrothermal mineralization, the sulphide ore bodies. The faint though distinct schistosity which is always parallel to that of the enclosing schist, and the numerous schist residuals in the green rock indicate that it has replaced the schist. It is thought that the green rock was formed by an intense ankeritic carbonatization of the schist within a general zone of tension. (The development of this zone will be described later in the description of the chalcopyrite lens.)

ORE BODIES.

The sulphide mineralization at the Eustis Mine has resulted in concentrations of chalcopyrite and pyrite in four lenses that follow the attitude of the enclosing schists. The strike of the schists and ore lenses is northeast and the dip, although it averages 45 degrees, ranges from horizontal to 80 degrees southwest. The amount of chalcopyrite in these lenses varies. In one lens, referred to as the chalcopyrite lens, chalcopyrite constitutes from 10 to 20 per cent. of the sulphide content, the greater part of

the remainder being pyrite. The other three lenses, which consist almost wholly of pyrite and contain less than one per cent. chalcopyrite, are known as the pyrite lenses. The four lenses are arranged *en echelon*. The chalcopyrite lens lies farthest to the southwest, each succeeding lens to the northeast being across the dip and below that lens on the southwest.

Chalcopyrite Lens.—The markedly high copper content of the chalcopyrite lens makes this the copper ore body of the Eustis; the pyrite lenses may or may not be mined, depending upon the company's desire for an increased production of pyrite. According to Snow and Brownbill,[5] "The copper lens varies in width from 6 feet to 40 feet, normal to the dip and strike, and averages 110 feet in length along the strike."

The chalcopyrite lens is entirely conformable to the schistosity of the enclosing schists. Cross-cutting was not observed by the writer; however, Dresser,[6] in describing the deposits of the Capleton Mine nearby says, "Though rarely, the ore bodies, occasionally, cross the planes of foliation of the country rock."

Generally the contact between ore and country rock is not sharply defined; it is transitional. In the vicinity of the contact narrow bands of schist up to 4 inches wide alternate with bands of sulphide, the amount of schist decreasing and the amount of sulphide increasing toward the ore lens. Within these lenses, however, horses of unreplaced country rock are common. These horses are in all stages of replacement, from those whose character is quite distinct, to those whose ancestry, in the case of the schists, is only detected by an indefinite banding preserved by the sulphides.

A striking feature of the chalcopyrite lens is that cross-sections of it, as shown by the plans on each level, are bounded, not by simple curves, but by sigmoid, or reverse, curves such as bound quartz lenses in the drag folds of folded rocks. All pairs of sigmoid curves are similarly oriented in the direction of curving wherever a section across the lens is chosen, whether in the upper

[5] Snow and Brownbill: *Op. cit.*, p. 76.

[6] Dresser, J. A.: Report on the copper deposits of the Eastern Townships of Quebec. Can. Geol. Surv., No. 974, p. 10, 1907.

or lower parts of the lens, or in wide or narrow sections. Such a sigmoid form is that assumed in the zone of tension resulting from the action of two opposite and tangential forces. Inasmuch as the strike of the lens is northeast, conforming to that of the schists, it will be evident that tangentially opposed forces directed towards each other from these two general directions, but at a small angle to the strike of the schists, would create a sigmoidally shaped zone of tension in the schists. It is thought that such a zone of tension was formed and and proved satisfactory for the ingress of ore-bearing solutions and the consequent deposition of the sulphides. The pyrite lenses were not studied in as much detail as the chalcopyrite lens, but their general form indicates that a similar explanation of origin is applicable. It is interesting to note that Williams,[7] in discussing the genesis of the Perrunal-La Zarza ore body, Spain, is of the opinion that the La Zarza ore body occupies a tension fissure.

Pyrite Lenses.—At present three pyrite lenses are known, but they have not been developed as completely as the chalcopyrite lens. They are thinner across the dip but are longer along the strike than is the chalcopyrite lens. These lenses lie northeast from the chalcopyrite lens and stratigraphically below it. None of these are, however, a continuation of the copper lens.

Faulting.—Faults are few and the displacements are small. The faults strike with the ore lenses, but they are steep and the major displacements are vertical; 30 feet is about the maximum vertical displacement. In addition to the major faults, the schists have been cut by steeply dipping joint planes from 2 to 18 inches apart, along which the schistosity has been slightly bent in the direction of the slippage; these are small normal faults. This type of faulting constitutes what is known locally as "back-structure." It is to be noted that these joints antedate the formation of both the green rock and the ore.

Mineralogy.—The metallic minerals found in the average Eustis ore are listed below in their order of paragenesis (those

[7] Williams, G.: The genesis of the Perrunal-La Zarza pyritic orebody, Spain. Inst. Min. Met. Trans., London, vol. 42, p. 27, 1933.

found in the metamorphosed ore on the 4,850-foot level will be described in Part II of this paper): arsenopyrite, pyrite, sphalerite, tetrahedrite and tennantite, chalcopyrite, galena.

Pyrite, chalcopyrite, sphalerite, and galena occur at all depths in the ore body; tetrahedrite and tennantite in a quartz vein a few hundred feet below the Slide Drift and in a quartz veinlet at 6,000 feet in the shaft as of July, 1933; and arsenopyrite only as a few euhedral grains in the ore on the 5,000-foot level. Pyrite and chalcopyrite are the most abundant. Pyrite forms approximately 95 per cent. of the sulphides in the pyrite lenses and approximately 80 per cent. in the chalcopyrite lens; chalcopyrite rarely exceeds 20 per cent., and averages 12 per cent., the ore running approximately 4 per cent. copper, which has usually been the run of the mine average. Sphalerite and galena occur only incidentally, never in amounts greater than one per cent. Because of the small amounts of these two sulphides, no conclusions as to their variations in depth could be made.

Microscopic study of the ore revealed two characteristic features of the pyrite. First, much of the ore is porphyritic in texture. This is evident in the hand specimen, and is noticeable in polished sections (Fig. 3). Large "phenocrysts" of pyrite are embedded in a groundmass of chalcopyrite and smaller pyrite grains. Second, the habit of the pyrite proved the absence of post-mineral deformation. Many of the pyrite grains possess perfect rectangular and triangular outlines in section (Fig. 4). The corners of these forms are very sharp, they have not been broken by deforming forces. Where these unbroken outlines are lacking, the grains are rounded and smoothed by the other minerals in the usual replacement manner. Furthermore, a study of the chalcopyrite grains did not disclose any evidence of post-mineral deformation. Etching of the more massive chalcopyrite revealed an equigranular texture with no tendency to elongation of the grains.

No definite information about the age of the arsenopyrite was obtained, but the euhedral nature of the small amount present suggests that it was the earliest sulphide to form. Replacement

veinlets of chalcopyrite in the pyrite indicate the earlier age of the pyrite. Examples of tetrahedrite replacing sphalerite, and of chalcopyrite replacing both these minerals, were seen. The mutual boundaries between the galena and its surrounding minerals make age relationships inconclusive; however, inasmuch as it is later than chalcopyrite in most ores, it is placed last in the paragenesis of the typical Eustis sulphides.

Numerous quartz-albite veinlets traverse the sulphides. Within massive chalcopyrite these veinlets were seen to traverse the grain boundaries of etched chalcopyrite.

Relation of the Ore Bodies to Sodic Rocks.

The ore bodies of the Eustis are intimately associated with sodic quartz porphyry. Although not in direct contact with it, they are enclosed by rocks derived from the porphyry. The evidence gained underground and from a study of thin sections indicates that the quartz porphyry grades through a schistose phase into the muscovite schist that surrounds the ore lenses. Undoubted replacement of the schist by the green rock indicates that the latter is genetically related to the porphyry.

The Eustis porphyry is quite sodic. In this connection it is interesting to note that sodic rocks have been found associated with the important pyritic deposits in the province of Huelva, Spain, in those of the Rödhammer type in Norway, and in Shasta county, California.

Sodic porphyries, which include quartz porphyry, trachyte porphyry, and syenite porphyry, cover a larger area than any other group of rocks in the province of Huelva. Collins[8] has classed the pyritic ore bodies of this province according to the nature of the wall rock. Of the forty-two ore bodies listed, more than half the number are either wholly in porphyries or at contacts between slate and porphyry; the remainder are in slates that lie close to porphyry.

[8] Collins, H. F.: The igneous rocks of the province of Huelva and the genesis of the pyritic orebodies. Inst. Min. Met. Trans., London, vol. 31, p. 81, 1922.

Of the three different types of pyritic deposits in Norway, one, the so-called Rödhammer type, carries abundant pyrite and is associated with the soda-rich granite, tröndhjemite.[9]

In the various copper districts of Shasta county, California, the country rock of the pyritic ore bodies is a definitely sodic alaskite porphyry. Graton[10] describes this condition as general for the various copper districts of Shasta county; and Boyle,[11] more specifically for the Bully Hill mining district in the same county, reaches similar conclusions.

Genesis of the Ore Bodies.

The ore bodies of the Eustis present features indicating that they were formed from hydrothermal solutions and not from aqueo-igneous melts. The varying stages of replacement of the schist and green rock by the ore solutions may be traced from massive ore with banding as an inheritance of the schistose texture of the schist, through ore containing residuals of country rock, to country rock containing only disseminated sulphides. Such evidence of a gradational process and absence of marked brecciation indicate the improbability of the ore bodies resulting from the injection of molten sulphides. It is to be noted also, that with the exception of that portion of the ore which has been locally metamorphosed, minerals indicating the necessary high temperature accompanying the intrusion of an injected molten mass are lacking; there are no metallic oxides, biotite, pyroxenes, or other high temperature minerals.

The action of large quantities of hydrothermal solutions is evidenced by the widespread development of muscovite in the schist, of ankeritic carbonate and chlorite to form the green rock, and of numerous veinlets containing quartz, albite, chlorite, and carbonate, in both the schist and the green rock. In favor of hydrothermal solutions in the formation of the Rio Tinto ore

[9] Williams, G.: *Op. cit.* Discussion, p. 650.

[10] Graton, L. C.: *Op. cit.*, p. 89.

[11] Boyle, A. C.: The geology and ore deposits of the Bully Hill mining district, California. Am. Inst. Min. Eng. Trans., vol. 48, p. 86, 1915.

bodies, Bateman describes the intense sericitization of the mineralized porphyry and slate bordering the ore and notes that, "All the rock-forming minerals have been replaced by sericite, the feldspar most and the quartz least. Residuals of quartz, partly penetrated by rods of sericite or embayed by a felted mass of sericite fibers lie wholly within the sericite."[12] Such textural evidence of hydrothermal replacement by muscovite prevails in the Eustis schist (Fig. 2).

There are no indications that the green rock or schist, either that surrounding the ore bodies or that now replaced by sulphides which preserve a banding parallel to the foliation of the schist, has at any time been severely sheared or shattered as would rock lying within a shear zone. Finlayson[13] and Bateman[14] advocated the replacement of sheared and crushed rock within a shear zone for the pyritic ore bodies of the Huelva district, Spain. With respect to the Eustis ore, however, the author considers that the sigmoid shape of the ore bodies indicates that the ore solutions replaced rock within a zone of tension rather than crushed rock within a zone of shearing.

The source of the Eustis ore solutions is unknown. It is thought that they did not come from the associated sodic porphyry but rather from its parent magma, a magma which, because of the association of other pyritic ore bodies with sodic porphyries, was of a type unique in characteristically giving off large quantities of pyritic solutions.

No information as to the age of the deposit has been gained during the present investigation.

METAMORPHOSED ORE BODY.

The heat accompanying the intrusion of a 40-foot camptonite dike on the 4,850-foot level has metamorphosed the Eustis ore

[12] Bateman, A. M.: Ore deposits of the Rio Tinto (Huelva) district, Spain. ECON. GEOL., vol. 22, p. 582, 1927.

[13] Finlayson, A. M.: The pyritic deposits of Huelva, Spain. ECON. GEOL., vol. 5, p. 434, 1910.

[14] Bateman, A. M.: *Op. cit.*, p. 613.

for a distance of approximately 10 feet from the dike to a sulphide aggregate in which the high-temperature sulphides, pyrrhotite and cubanite, predominate, and in which anthophyllite is the common gangue mineral.

Two features indicate that the dike is later than the main ore body. First, it has dense border phases in contact with either ore or schist; and second, it occupies a fault that has definitely displaced the ore lens, although the displacement is only a few feet.

Ore Gangue.

The gangue that accompanies the pyrrhotite and cubanite is entirely different from that of the main ore body. The orthorhombic amphibole, anthophyllite, is the predominant silicate. Of the ordinary gangue the only minerals present are imperfect quartz phenocrysts, feather quartz, and calcite. The anthophyllite replaces both types of quartz, thereby indicating that, since the feather quartz is later than the pyrite of the main ore body, the anthophyllite is later than this sulphide. Calcite is, however, later than the anthophyllite.

Anthophyllite is less abundant in the country rock than in the ore. In the material examined the anthophyllite areas consist of cloudy, fibrous material, and their outline and size simulate the areas occupied by the muscovite and chlorite of the ordinary mineralized schist. This habit suggests that the muscovite and chlorite contributed in part at least to the formation of the amphibole.

Pyrrhotite and chalcopyrite definitely replace the anthophyllite. In sections showing abundant gangue, the pyrrhotite and chalcopyrite occur in thin veinlike aggregates that curve and interleave with the anthophyllite fibres (Fig. 5). Pyrite antedates and does not replace the anthophyllite. It represents the pyrite that was not converted into pyrrhotite under the influence of the heat emitted by the intruding dike.

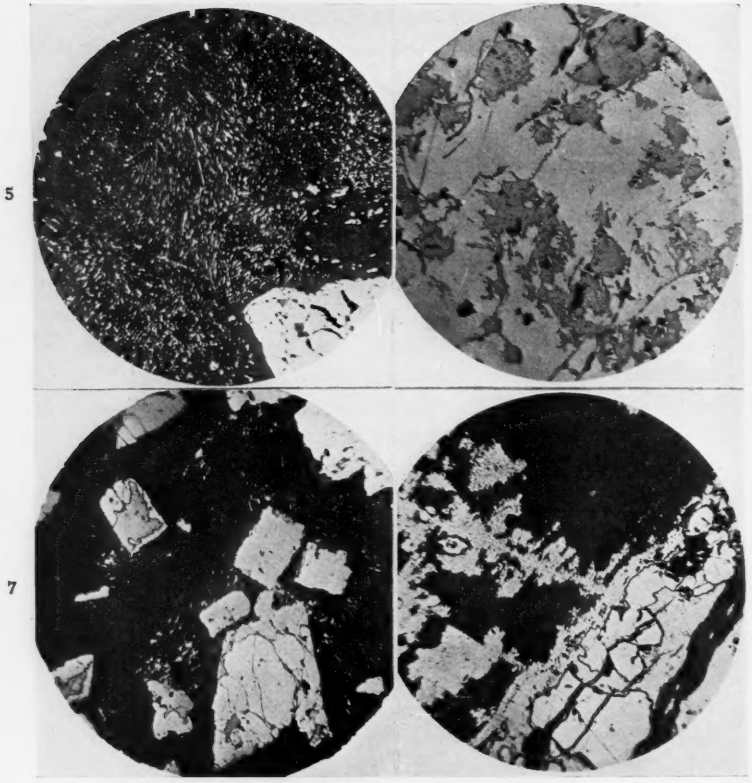

FIG. 5. Anthophyllite (black) replaced by stringers of chalcopyrite and pyrrhotite (light grey). Cube of pyrite in lower right. × 45.

FIG. 6. Characteristic replacement of pyrrhotite (dark grey) by chalcopyrite (lighter grey). × 45.

FIG. 7. Pseudomorphic pyrrhotite (grey) after pyrite (light grey). × 19.

FIG. 8. Arborescent chalcopyrite (light grey) projecting from sulphide mass (lower right) into dike (black). Note thin medial line of white chalcopyrite. × 19.

Average Composition of the Sulphide Masses Containing Pyrrhotite but not Cubanite.

Pyrrhotite occurs in all the ore adjacent to the dike but cubanite is present only in patches. The average mineral composition of the ore lacking cubanite is shown immediately below; that containing cubanite will be described later: pyrite 2 per cent.; chalcopyrite 57 per cent.; pyrrhotite 36 per cent.; gangue 5 per cent.

The pyrite of this material mostly occurs as well-rounded grains, the sharp cubic forms which characterize the pyrite of the ordinary ore being conspicuously absent. The numerous reticulating veinlets of all the other minerals in the pyrite, and the many smooth and rounded contacts of all the pyrite grains, indicate that the pyrite has been replaced by pyrrhotite, chalcopyrite, and the gangue minerals.

The pyrrhotite, in those specimens that do not contain cubanite, occurs as irregular areas, as jagged promontories projecting from these, and as smaller areas or islands clustering around the main mass (Fig. 6). In most cases the above three units of any one area of pyrrhotite constitute but one crystal in varying degrees of replacement by the surrounding minerals. Polarized light serves to delimit the pyrrhotite crystals. Replacement veinlets of chalcopyrite in the pyrrhotite are common; these are most numerous in the immediate vicinity of the dike where there is a greater concentration of chalcopyrite.

Chalcopyrite forms a matrix for the areas of pyrrhotite. Etching with a hot acid solution of potassium dichromate indicates that the texture is granular, and that evidence of shearing is absent. Numerous thin replacement veinlets of chalcopyrite definitely cut across the boundaries of pyrrhotite crystals in the same manner that the quartz-calcite replacement veinlets transect the chalcopyrite crystals.

One of the most interesting features of the mineralized schist adjacent to the dike is the presence of perfect pyrrhotite pseudomorphs after pyrite (Fig. 7). In some cases the replacement

is so perfect that no pyrite remains, in others there are a few pyrite residuals. Commonly the replacing mass includes a small amount of chalcopyrite that replaces the pyrrhotite.

The granularity of the pyrrhotite is apparently the same as that of the replaced pyrite, for in many areas a rectangular pseudomorph of pyrrhotite consists of but a single grain and irregular larger areas contain as many as three grains, suggesting that these areas originally consisted of an aggregate of pyrite grains. This conformity in grain to that of the original mineral is characteristic of pseudomorphic replacement.

Feather-shaped areas of marcasite have formed in the ore close to the dike. Many of the marcasite masses are cut medially both by quartz-carbonate and by chalcopyrite veinlets. The undoubted hypogene origin of these later veinlets suggests that the marcasite is hypogene rather than supergene. The association with quartz-carbonate veinlets suggests also that the solutions were probably slightly alkaline, possibly neutral, when the marcasite was formed. Newhouse [15] ascribes a hypogene origin to marcasite associated with quartz and carbonate found at Kokomo, Colorado. The marcasite occurs 3,300 feet vertically below the outcrop and it is unlikely that supergene marcasite would form at such a great depth from the surface.

Where in contact with the ore body, the dike is bordered by narrow quartz-carbonate stringers and generally by a band of chalcopyrite (0.5 mm. wide) in which there is little pyrite or pyrrhotite. For approximately a quarter of an inch from the contact the dike is permeated by some disseminated chalcopyrite and by distinctively arborescent masses of chalcopyrite that project from the main chalcopyrite ore (Fig. 8). The fringes of these arborescent masses are commonly clouded by numerous gangue residuals, but the medial line is solid chalcopyrite; this probably represents the filling of a clean cooling fracture in the dike. Pyrrhotite does not occur within the dike. This is probably because only the last sulphide to crystallize from solid solution, chalcopyrite, permeated the dike.

[15] Newhouse, W. H.: Paragenesis of marcasite. ECON. GEOL., vol. 20, pp. 54–66, 1925.

Cubanite.

Large amounts of cubanite, associated with pyrrhotite, chalcopyrrhotite, and pyrite, were found in small masses of unstoped ore about 18 inches from the dike. The approximate sulphide percentage in those specimens containing the greatest amount of cubanite are: cubanite 63; chalcopyrite 20; pyrrhotite 10; pyrite 2.

Cubanite never occurs as irregular massive areas, but as well-defined blades that range in length from 3 mm. to 0.2 mm. and in width from 0.07 mm. to hair lines under high magnification (Fig. 9). The variation in width is, of course, partly due to

FIG. 9 (Left). Cubanite; showing meshwork texture. Polarized reflected light. × 19.

FIG. 10. Vermicular veinlets of pyrrhotite (black) lying between 3 adjacent areas of cubanite blades (white) from which they have exsolved. Note narrowing of veinlets where they join in lower center. Stippled areas are early pyrrhotite. × 110.

the different angles at which the plates are cut by the polished sections. The pattern displayed by the cubanite laths may be described as an openly-woven meshwork, the chalcopyrite occurring between the laths or bundles of laths in whatever spaces happen to be available.

Evidence suggests that the cubanite is exsolved from the chalcopyrite. A noticeable feature is that any one lath of cubanite con-

fines itself to but one crystal of chalcopyrite, indicating that its extension is obviously controlled by the boundaries of a chalcopyrite grain. Such a habit has been attributed to exsolution in examples described by Schwartz,[16] Ramdohr,[17] Schneiderhöhn,[18] Newhouse,[19] and others.

Experimental data indicate that a solid solution of chalcopyrite and cubanite forms above 400° C.[20] This suggests that the heat incident upon the intrusion of the camptonite dike raised the temperature of the immediately adjacent sulphide to 400° C. or more.

The process of exsolution may have been as described by Newhouse,[21] "The solid solution which was very rich in iron as compared with pure chalcopyrite, on cooling unmixed with the segregation of chalcopyrite and cubanite. The cubanite-rich portions, such as the areas showing intergrowths of cubanite and chalcopyrite, and also individual laths of cubanite, unmixed to form cubanite and pyrrhotite."

An approximate analysis of the two types of sulphide aggregates, that with and that without cubanite, was made by determining the percentage by area of the minerals on the polished surface, converting this to a mineral composition by mass and, by assuming ideal compositions for the sulphides, obtaining the amount of iron, copper, and sulphur present in each type. The amounts of iron, copper, and sulphur were substantially the same in each type of sulphide aggregate, thus demonstrating that, in the development of cubanite, there had been neither gain nor loss of the constituent elements. The system pyrite-chalcopyrite-pyrrhotite-cubanite was, for this locality, apparently closed; there-

[16] Schwartz, G. M.: Intergrowths of chalcopyrite and cubanite. ECON. GEOL., vol. 22, pp. 44–61, 1927.

[17] Ramdohr, P.: Beobachtungen an Chalmersite. Metall u. Erz., Bd. 22, pp. 471–474, 1925. Ramdohr, P.: Neue microskopische Beobachtungen an Cubanite, etc. Zeitschr. prakt. Geologie, vol. 36, pp. 169–178, 1928.

[18] Schneiderhöhn, Hans, and Ramdohr, P.: Lehrbuch der Erzmikroscopie, vol. 2, pp. 360–367, 1931.

[19] Newhouse, W. H.: A pyrrhotite-cubanite-chalcopyrite intergrowth from the Frood Mine, Sudbury, Ontario. Am. Min., vol. 16, pp. 334–337, 1931.

[20] Schwartz, G. M.: *Op. cit.*

[21] Newhouse, W. H.: *Op. cit.*, p. 337.

fore from the original pyrite-chalcopyrite aggregate, cubanite could have formed only by exsolution.

Pyrrhotite Veinlets.

The pyrite and chalcopyrite of the cubanite areas are similar in every respect to that found in the non-cubanite areas. The pyrrhotite is, however, different. Rounded bleb-like areas are few and small, but short irregular veinlets are very common (Fig. 10). These occur between the chalcopyrite grains and around the ends of the cubanite blades; they never cross grain boundaries. Another constant feature of these veinlets is that where two or more join together the width of each is narrower at the junction than elsewhere along the veinlets (Fig. 10). The pyrrhotite of these veinlets is in the form of small acicular crystals arranged approximately normal to the walls of the veinlet. The pyrrhotite in the few rounded blebs present, however, is coarser-grained and equigranular in texture. Although the acicular habit is that of valeriite, the pyrrhotite does not possess the marked anisotropism of valeriite.

The pyrrhotite veinlets may represent one of three types, viz.: (1) Later hydrothermal material, cutting and replacing both chalcopyrite and cubanite. (2) Residual veinlets of pyrrhotite after chalcopyrite and cubanite. (3) Exsolved material from the chalcopyrite-cubanite intergrowth.

Militating against a classification with the first type is the fact that none of the pyrrhotite veinlets transect crystals of either chalcopyrite or cubanite; they are in all cases intergranular.

Two characteristics invalidate classifying with the second type. First, the grain size of the pyrrhotite in the veinlets is much smaller than that of the bleb-like areas. Second, the tendency of replacing chalcopyrite as seen in the sections previously described is to reduce pyrrhotite areas first to promontories, then to groups of islands, and finally to small isolated masses. A veinlet stage is never present in this replacement process.

All the evidence suggests that the pyrrhotite veinlets represent exsolved material from the chalcopyrite-cubanite intergrowth.

Most important is the fact that the pyrrhotite veinlets are intergranular. In this connection Van der Ween [22] says,

"In normal cases in metallography with metallic solutions, with very slow cooling we may assume that segregation of the new phase which is thrown out first, starts at the boundaries of every grain and that gradually every grain will become surrounded by a layer or film of this substance. Then the texture of the section looks like a 'network' (network texture, cell texture) of these films around the grains," and further, "Sometimes this texture is called secondary or tertiary in metallography. Similar network textures we have sometimes in magmatic deposits, *e.g.*, in some specimens of nickeliferous deposits. The grains of pyrrhotite are surrounded by pentlandite (Fig. 15)."

The striking similarity of the texture developed where pentlandite separates out of pyrrhotite on cooling, as is shown by Van der Ween's Figure 15, to the texture as seen between the pyrrhotite and chalcopyrite-cubanite as above-described from the Eustis, indicates that the two have a similar origin. That is, if, as postulated by Van der Ween, the texture displayed by pentlandite is due to exsolution, then by textural analogy, that displayed by pyrrhotite in the cubanite specimens of the Eustis is also due to exsolution.

Earlier masses of pyrrhotite and later veinlets of it in chalcopyrite-cubanite intergrowths have been described from Parry Sound, Ontario,[23] and from Fierro, New Mexico,[24] by Schwartz. His remarks concerning the crystallization of material from an iron-rich chalcopyrite solution are significant. He says, "An excess of iron and sulphur crystallized as pyrrhotite, perhaps at somewhat lower temperatures, and slightly later than the chalcopyrite and cubanite solid solution. The pyrrhotite at Fierro obviously crystallized later than the chalcopyrite-cubanite intergrowth." [25]

[22] Van der Ween, R. W.: Mineragraphy and ore deposition. The Hague, vol. 1, p. 25, 1925.

[23] Schwartz, G. M.: Primary relationships and unusual chalcopyrite in copper deposits at Parry Sound, Ontario. ECON. GEOL., vol. 19, p. 211, 1924.

[24] Schwartz, G. M.: Chalmersite at Fierro, New Mexico. ECON. GEOL., vol. 18, p. 275, 1923.

[25] Schwartz, G. M.: Intergrowths of chalcopyrite and cubanite. ECON. GEOL., vol. 22, p. 52, 1927.

In the Eustis occurrence the common and marked narrowing of the pyrrhotite veinlets at the point where two or three join one another is considered evidence in support of unmixing. The narrowing of the veinlets at a junction of two or more is one of the criteria used by Schwartz [26] in recognizing material that has unmixed from solid solution.

The present writer [27] has also described such a narrowing of pyrrhotite veinlets in specimens of copper ore from the Waite-Ackermann-Montgomery mine in Quebec. These veinlets were considered to have formed as the result of unmixing.

Sequence of Events in the Formation of the Metamorphosed Ore Body

The heat accompanying the intrusion of a 40-foot camptonite dike has metamorphosed the chalcopyrite ore body of the Eustis mine. The following are the results:

(1) The ore and country rock were heated up to a temperature of 400° C. or more by the intrusion of the dike.

(2) Anthophyllite developed, the constituents of both gangue and sulphides possibly contributing to its formation.

(3) The heat was sufficient to cause the chalcopyrite and some of the pyrite to form a solid solution of iron-rich chalcopyrite. As cooling proceeded, the chalcopyrite solid solution purged itself of excess iron giving, first, early pyrrhotite, then chalcopyrite containing less iron, then cubanite. Further cooling resulted in the later pyrrhotite veinlets exsolving from the chalcopyrite and cubanite. Overlapping, undoubtedly, interrupted the perfect sequence of these events. It is probable that replacement of the pyrite in the schist by pyrrhotite and chalcopyrite pseudomorphic aggregates occurred at this time as well as the deposition of late chalcopyrite in the dike as disseminated grains and as arborescent areas in transverse fractures that are regarded as cooling fractures.

[26] Schwartz, G. M.: Textures due to unmixing of solid solutions. ECON. GEOL., vol. 26, pp. 761–762, 1931.

[27] Stevenson, J. S.: Vein-like masses of pyrrhotite in chalcopyrite from the Waite-Ackermann-Montgomery Mine, Que., Am. Min., vol. 18, p. 448, 1933.

(4) The formation of marcasite occurred early in the sequence, after the early pyrrhotite but before the last of the chalcopyrite; although no conclusive evidence was found, it probably formed by hydrothermal processes rather than by exsolution.

(5) Late carbonate-quartz veinlets have been the last manifestation of hydrothermal action.

GENERAL SUMMARY.

The Eustis ore bodies occur in muscovite schist and a massive carbonate rock, "green rock," which has formed by replacement of the schist. The schist itself has resulted from the metamorphism, mainly by shearing stresses, of a sodic quartz porphyry that is found underground to within 500 feet of the ore bodies. The association of pyritic ore bodies and sodic rocks occurs also in the deposits of southern Spain, Norway, and Shasta county, California.

A study of the chemical analyses of the three genetically related rocks and of the absolute gains and losses per cubic meter of rock indicates that the chemical changes involved in the derivation of the green rock from the muscovite schist were much more intense than those in the derivation of the schist from the porphyry. Such characteristics, together with the occurrence of the green rock close to the ore bodies, indicate that the carbonate rock has been formed largely by the effect of hydrothermal solutions on the schist.

The ore bodies of the Eustis mine comprise four lenses of pyritic ore arranged *en echelon* in the enclosing schist and extending continuously down the dip for 6,500 feet to the present depth of mining;[28] how far they go beyond this is unknown. One lens, referred to as the chalcopyrite lens, contains 10 to 20 per cent. chalcopyrite, most of the remainder being pyrite; the other three lenses, referred to as the pyrite lenses, are mostly pyrite, containing less than one per cent. chalcopyrite. The general sigmoid shape possessed by nearly any cross-section of a lens, especially of the chalcopyrite lens, indicates that the ore bodies

[28] Snow, F. W., and Brownbill, H. F.: *Op. cit.*, p. 76.

occupy a pre-existing zone of tension in the schist rather than a zone of shearing. Post-mineral deformation of the sulphides is absent; perfectly shaped and unbroken cubes of pyrite are characteristic of all polished sections containing pyrite.

In the immediate vicinity of a 40-foot camptonite dike on the 4,850-foot level, the chalcopyrite ore body has been largely metamorphosed to an aggregate in which the high temperature minerals pyrrhotite, cubanite, and anthophyllite predominate. Exsolution from a solid solution of pyrite and chalcopyrite is thought to have been an important process in the formation of the pyrrhotite and cubanite.

Although the source of the ore solutions is unknown, it is thought that they came, not directly from the quartz porphyry, but from a common magma; a magma characterized by the ability to yield sodic rocks and associated pyritic ore bodies.

ACKNOWLEDGMENTS.

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DEPARTMENT OF MINES,
VICTORIA, BRITISH COLUMBIA,
January, 1937.

ORIGIN OF THE BEDDING REPLACEMENT DEPOSITS OF FLUORSPAR IN THE ILLINOIS FIELD.

L. W. CURRIER.[1]

ABSTRACT.

The banded fluorspar deposits of the Cave In Rock district are attributed to replacement of limestone and the preservation of bedding and cross-bedding of the rock. The solutions contained hydrofluoric acid which reacted with $CaCO_3$. The replacement was stoichiometrical, with consequent reduction of volume, but continued deposition of calcium fluoride, brought in from other points, partly or completely filled the voids. Thus, the pure bands display a comb structure, and represent replacement of pure limestone laminæ. The less pure granular bands, devoid of comb structure, reflect the alternating, impure bands of the rock in which the fine-grained impurities (ferriferous carbonate, clay, et al) were disseminated. Recrystallization of clastic quartz grains in some calcareous sandstone layers resulted in the formation of bands of quartz grains. The writer dissents from the views of Bastin who believes the banding is due to rhythmic precipitation. Chemistry and controlling structural conditions are discussed.

The Cave In Rock district of the Illinois fluorspar field is particularly noted for the occurrence of fluorspar as horizontal, tabular and lenticular replacement bodies in certain beds of thick Mississippian limestones. Unlike fluorspar deposits in the rest of the Illinois-Kentucky field, the Cave In Rock deposits are not directly connected with major normal faults, but appear to owe their localization to a combination of geographic, stratigraphic, and minor structural features. Moreover, the texture and banded character of the deposits are decidedly individualistic. Their pronounced banded character and relationship to very minor fissures and relatively impervious cap rocks have led to the interpretation that they represent replacement by diffusion and rhythmic

[1] Published by permission of the Director of the United States Geological Survey, and the Chief of the Illinois State Geological Survey.

deposition.[2] The present writer dissents from the views attributing importance to diffusion phenomena as the chief cause of the banding, and ascribes their origin to progressive replacement along bedding planes and cross-bedding laminæ of the limestone; the alternation of pure and impure bands is believed to reflect original differences in texture and composition of the host rock, and the prevailing comb structure of the pure bands is attributed to a stoichiometrical balance with attendant decrease of volume.

This paper is based upon data recently obtained in a cooperative investigation carried on by the United States Geological Survey and the Illinois State Geological Survey. The work was initiated in 1935 as a project of the Public Works Administration, and in 1936 was continued and carried to completion by the two Surveys. The writer is indebted to several colleagues for helpful discussions regarding the theoretical points involved.

THE ILLINOIS-KENTUCKY FLUORSPAR FIELD.

Pope and Hardin counties in Illinois, and Crittenden, Livingston, and Caldwell Counties in Kentucky comprise the Illinois-Kentucky fluorspar field, which has been notable for many years as the world's largest fluorspar producing area. In brief, the areal geology shows it to be underlain by a thick series of Mississippian sedimentary formations, intersected by numerous basic dikes—chiefly peridotites—and sills, and broken by many normal faults whose displacements range up to 1,300 feet or more. The geologic map of the entire area (Fig. 1) suggests a broad oval-shaped dome about 30 miles long and 20 miles wide, that has collapsed by intricate faulting.

The Cave In Rock district lies in the eastern part of the Illinois portion of the field, near the border zone of the structural dome, and about 4 miles northwest of Cave In Rock, a town on the Ohio River about 10 miles above Rosiclare, for many years the

[2] Bastin, E. S.: The fluorspar deposits of Hardin and Pope Counties, Illinois. Ill. State Geol. Surv., Bull. 58, pp. 49–55, 1931. Also: XVI International Geological Congress, Guidebook 2, pp. 39–41, 1932.

center of the fluorspar industry in Illinois. Except in the Cave In Rock district the fluorspar deposits consist of veins in some of the fault fissures. The veins also carry subordinate amounts of sulphide minerals, chiefly galena and sphalerite, which in places

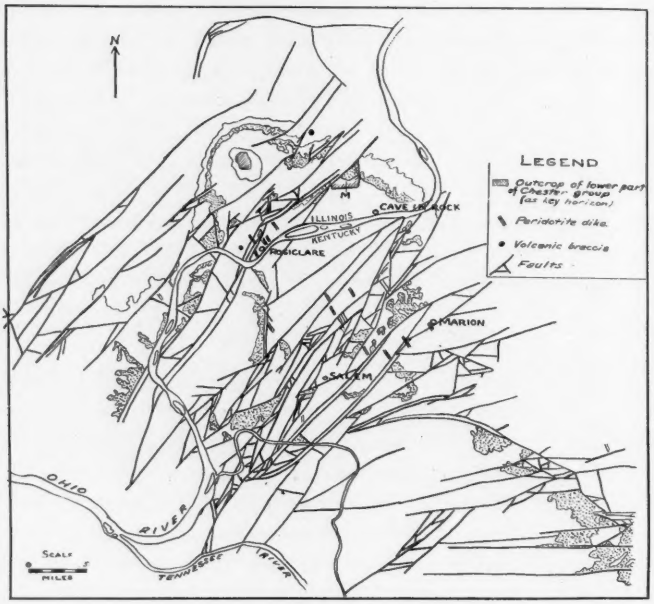


FIG. 1. Outline map of Illinois-Kentucky fluorspar field. Geology by Stuart Weller, A. H. Sutton, and Charles Butts, condensed from compiled map, courtesy of J. M. Weller. Area marked *M*, indicated about four miles northwest of Cave In Rock, is Cave In Rock district as recently mapped.

have been marketed as by-products of the fluorspar mining industry. The deposits are generally believed to be of hydrothermal origin directly or indirectly connected with the igneous rocks of the region.

The major geologic features of the field and of the deposits has been described in detail in several publications.[3]

GEOLOGY OF THE CAVE IN ROCK DISTRICT.

The Cave In Rock district, as mapped for the recent study, includes an area of about 3 square miles in the eastern part of Hardin County. The underlying formations are indicated by the following stratigraphic column:

CONDENSED STRATIGRAPHIC COLUMN FOR ILLINOIS-KENTUCKY FLUORSPAR FIELD (U. S. GEOL. SURVEY NOMENCLATURE).

Carboniferous system	Pennsylvanian series		Pottsville formation (sandstone and conglomerate)
	Mississippian series	Chester group	Alternating limestones and sandstones with a few shale beds. Fourteen formations, ranging from 20 feet to 175 feet thick. Group nearly 60 per cent limestone. Bethel sandstone at base.
			Ste. Genevieve limestone Ohara limestone member, 40–120 feet Rosiclare sandstone member, 2–40 feet (shale base toward east) Fredonia limestone member, (oolitic), 180–200 feet
		Meramec group	St. Louis limestone 350 ± feet Warsaw limestone 250 ± feet
			Osage formation 550 ± feet
Devonian or Carboniferous			Chattanooga shale 400 ± feet
Devonian system			Limestone (unnamed for this area)

The fluorspar bodies occur in the Fredonia limestone member, chiefly at its contact with the overlying Rosiclare sandstone mem-

[3] Bain, H. F.: The fluorspar deposits of southern Illinois. U. S. Geol. Surv., Bull. 255, 1905. Ulrich, E. O., and Smith, W. S. T.: The lead, zinc, and fluorspar deposits of western Kentucky. U. S. Geol. Surv. Prof. Paper 36, 1905. Weller, Stuart, and associates: Geology of Hardin County. Ill. State Geol. Surv., Bull. 41, 1920. Weller, Stuart: Geology of the Golconda Quadrangle. Kentucky Geol. Surv., ser. 6, vol. 4, 1921. Currier, L. W.: Fluorspar deposits of Kentucky. Kentucky Geol. Surv., ser. 6, vol. 13, 1923. Bastin, E. S.: *Op. cit.*

ber, the base of which in this area is a shale bed a few inches to about 2 feet thick. Minor mineral bodies have been found also, however, beneath a sub-Rosiclare stratum of calcareous sandstone, and at least one dense limestone stratum, from 20 to 40 feet below the chief fluorspar horizon. The Rosiclare sandstone and the main mineral horizon are exposed about midway up the slope of a southward and southeastward facing escarpment that separates the north and northwest mesa-like portion of the district from the south and southeast flat, sink-hole portion. In the southwest part of the district a small butte capped by Rosiclare sandstone represents a detached portion of the "mesa," and in this butte (Lead Hill) fluorspar bodies have been exploited. Most of the principal mines of the district have been developed through adits at the base of the sandstone, along the escarpment. Two mines have been established on the summit of the "mesa" a few hundred feet from the escarpment, through shafts about 160 feet deep. The Bethel sandstone forms the cap rock of the "mesa" in the developed area, and all formations have a slight general north to northeast dip. A few faults of very small displacement —for the most part not discernible from outcrops—cut the mineralized area. A major fault zone (Peters Creek fault) that trends N. 45° to 50° E. bounds the district on the west and northwest.

THE FLUORSPAR DEPOSITS.

Type and Form.—The fluorspar deposits are replacement masses in and along certain limestone beds. Although the term "blanket" has been applied to these deposits, the writer prefers to call them "bedding replacement" or more simply "bedding" deposits, as originally used in 1920.[4] "Blanket," as used in ore deposit nomenclature, has in part a distinctly different significance; moreover it has been used by miners in the fluorspar district to denote "gravel" deposits derived by disintegration and condensation of vein deposits in the clay overburden. The term "bedded" has been rejected because it connotes a syngenetic superficial process of concentration.

[4] Currier, L. W.: Ill. State Geol. Surv., Bull. 41, *Op. cit.*, p. 254.

In a broad way the fluorspar bodies are elongated tabular and lenticular masses whose long axes for the most part are generally parallel to the local structural trends and axes. The limits of the mined portions are commonly economic and merge into intervening belts too thinly mineralized for exploitation. In places,

FIG. 2. High-grade fluorspar specimen showing central line of vugs in the purer bands.

however, barren areas separate and border mineralized belts. The limits of mineral bodies are ordinarily marked by a progressive thinning of mineralization as well as by increase in impurity.

In a few places, mushroom-shaped " ore " bodies were observed which in cross section displayed tabular bedding deposits extend-

ing laterally from rather narrow, vertical, fissure veins; the veins extended downward into the drift floors, and either terminated upward at the shale roof, or were represented in the roof by one or more very thin veinlets—" roof veins."

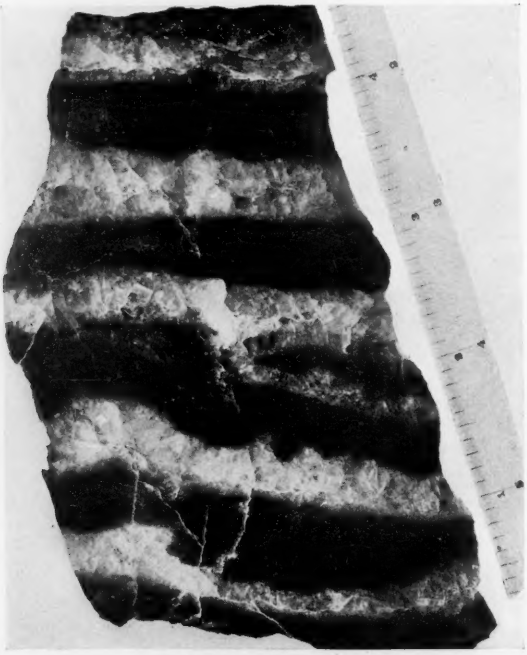


FIG. 3. Polished surface of high-grade fluorspar specimen; fluorspar content in excess of 90 per cent. The central lines of vugs in the purer bands are almost entirely filled in this specimen.

Structural Relations of Mineral Bodies.—The structural relations were studied in part by construction of a contour map of the base of the Rosiclare sandstone, which is the prevailing cap rock of the principal ore horizon. Thickness of the underlying adjacent mineralized zone was plotted to determine relations of

"ore" bodies to irregularities of the cap rock. The contours indicated local minor folds and warpings consistent with the regional axes. The thickest mineral bodies were found to be lo-

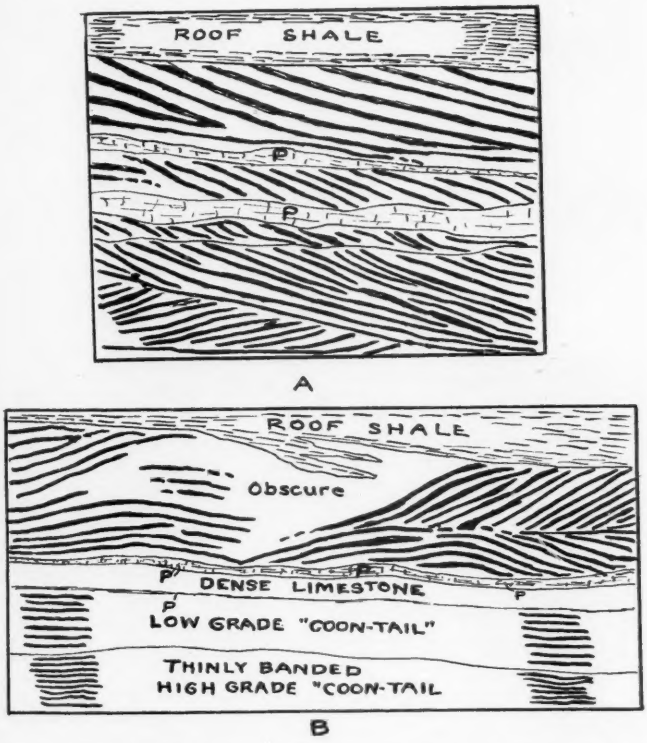


FIG. 4. Sketches of exposed fluorspar masses to show attitudes of bands. Heavy black lines represent impure bands; intervening white bands represent pure bands, which in places follow persistently along shale and limestone contacts. P = partings of shaly material or argillaceous limestone. In *B* the bands of the two lower beds of "coon-tail" ore maintain a remarkable degree of persistency and uniformity. Scale, 1 inch = 1½ feet, approx. Note, in both sketches, the indicated bifurcation and discontinuity of certain bands.

cated upon or to follow the steeper dips of the roof, and the crests and troughs of the narrower local folds. In general, broad horizontal areas showed weakest mineralization. In most

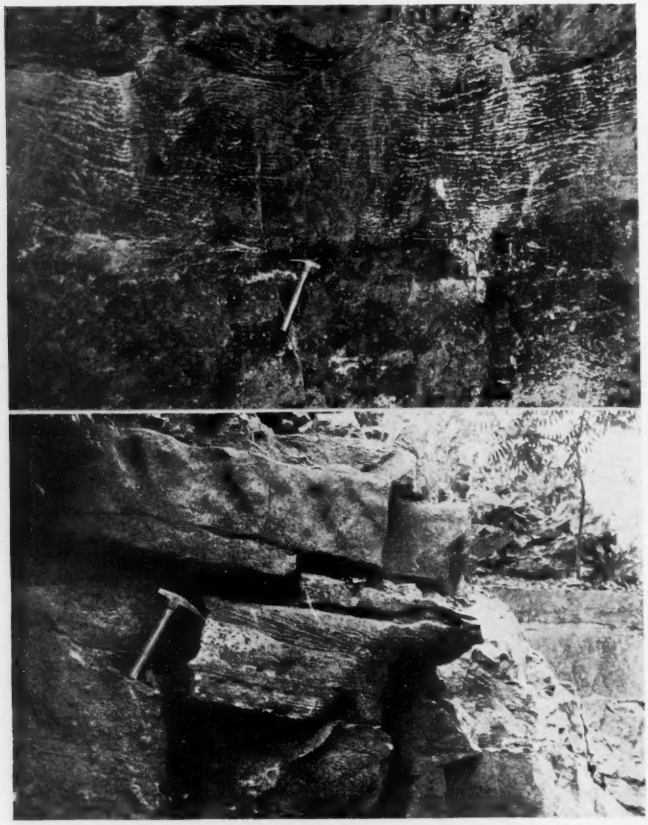


FIG. 5. Underground working face of banded fluorspar, Victory Fluorspar Co., No. 1 mine.

FIG. 6. Weathered exposure of Fredonia limestone at a cut near portal of Green mine, Benzon Fluorspar Co., Spar Mountain, showing bedding and cross-bedding laminations.

cases, the trends of roof veins, axes of folds, axes of thickest mineral bodies, and linear elements of regional deformation (Peter's Creek major fault, and several parallel or transverse minor faults) were found to be concordant. The details will appear in a forthcoming report on the district. In some of the mines it is an established rule to follow the roof veins in development.

Texture of the Deposits.—The Cave In Rock fluorspar deposits are characterized by exceptionally well developed banding. Photographs of the usual commercial materials are shown in Figs. 2 and 3 and in Fig. 5 a photograph of an underground working face is shown. The material mined consists typically of alternate bands of relatively coarse-grained crystalline florspar, and finer-grained, granular, " impure " material. The coarse bands commonly show well developed comb structure with more or less central lines of vugs or tabular cavities into which well formed crystals of fluorspar project. In many bands the central cavities are almost completely filled but the vug line is clearly discernible upon close examination, by means of crystal faces and a narrow band of more deeply colored (purple) fluorspar. The finer, relatively impure, bands are commonly gray or brown, and their granularity appears to preserve the original texture of the replaced limestone. Definite pseudomorphs of oolites and fossils are sometimes found. To the eye the " impure " bands appear to be mostly country rock material; however, they are composed chiefly of fluorspar and in places contain more than 80 per cent. of this mineral, so that separation of the two kinds of material by milling is not necessary. Under the microscope they are seen to contain remnants of unreplaced carbonates, limonite, and minute crystals of quartz. The total amount of silica is generally small and well below the commercial limit. The bands vary in thickness from a small fraction of an inch to several inches, probably averaging a half inch to three-fourths of an inch and to these contrasting bands is due the term " coon-tail spar " applied to the typical commercial fluorspar.

In one part of the area, bands of pure crystalline fluorspar alternate with bands of quartz, either as pure quartz crystals in comb structure, or finely granular quartz replacing original rock texture. Such material is not commercial but fortunately is very limited and restricted in occurrence.

FIG. 7. Bedding and incipient mineralization in Fredonia limestone at an adit portal, Spar Mountain. Hammer head at contact of roof shale and limestone. Incipient mineralization as white streaks parallel to bedding.

In part the bands are remarkably uniform in thickness, purity, and horizontal continuity. In places they vary in width, and attitude and their appearance closely simulates cross-bedding (Fig.

4). When traced, the bands are seen to die out by (1) thinning, (2) by truncation, and (3) by bifurcation. The entire mineralized bed also thins out in places between the roof shale and floor "rolls" of dense unreplaced limestone. These "rolls" or risers are frequently found to impose economic limits on the mineral bodies.

Short irregular, bifurcating and anastomosing veinlets of clear crystalline fluorspar occur in the shale roof at a few places, largely

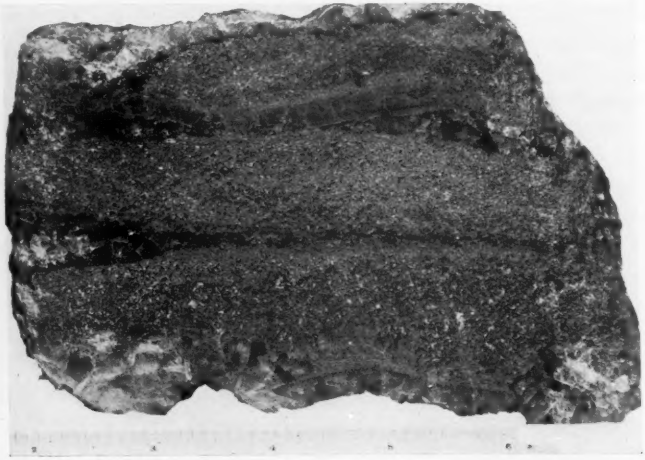


FIG. 8. Low-grade material, showing original rock bedding, thinning of fluorspar bands, and abundant granular relics of unreplaced ferriferous carbonate.

penetrating along bedding planes and in part isolating fragments of the shale. Such material is generally found in places of marked deformation of the roof.

In some places just below the roof extensive tabular cavities are lined with exceptionally large crystals of fluorspar.

Unmineralized thin beds of dense limestone or shaly material are commonly found as partings within fluorspar bodies. These

range in thickness from a fraction of an inch to two or three feet. The thicker limestone partings are cracked in places and crossed by thin veinlets of the mineral.

Related Textures of the Limestone Country Rock.—Weathered exposures of the upper part of the Fredonia limestone member show variability in texture and porosity, variability in composition, well marked stratification, and well marked cross-bedding (Figs. 6 and 7). The textures vary from very dense material that breaks with a sub-conchoidal fracture to obviously granular material composed of carbonate grains, oolites, fossil fragments, and sandy streaks. In a few places some of the laminæ are very arenaceous and are more rightly termed sandy limestone or calcareous sandstone.

Weathering may make differences in texture obvious by solution of the purer carbonate material, and oxidation of the ferruginous portions. Some of the residual carbonate grains in impure fluorspar bands are clearly ferriferous, probably ankeritic (Fig. 8).

Other Minerals of the Deposits.—Besides quartz and calcareous carbonates, accessory minerals in the fluorspar deposits include barite, galena, marcasite, chalcopyrite, and sphalerite. This assemblage is similar to that of the vein deposits, but the sulphides and barite are much less abundant, and need not be further considered for the purposes of this paper. Their occurrences have been adequately described in Bastin's paper.[5]

ORIGIN OF THE DEPOSITS.

The Fluorspar Field.—The fluorspar of the Illinois-Kentucky field, including the Cave In Rock district, is believed to have been deposited from ascending thermal solutions, directly or indirectly connected with the numerous mica-peridotite and lamprophyre dikes and sills that give this part of the Mississippi Valley distinction. The origin has been discussed in several earlier papers by Bain, Ulrich and Smith, Bastin, and Currier, references to which have already been cited in this paper.

[5] *Op. cit.*, pp. 60–63.

The writer is inclined to attribute the formation of the highly faulted structural dome of the Illinois-Kentucky field to regional crustal adjustment because the pattern of block faulting does not appear to accord with adjustments required by local uplift due to deep-seated magmatic intrusion. This matter is discussed in the forthcoming report of the Illinois Geological Survey and need not be considered further in this paper. The Cave In Rock district occupies a peripheral position on the northeast side of the dome, and this localization is deemed significant for reasons that appear below.

Lindgren [6] places the deposits in the mesothermal class.

The exceptional concentration of fluorspar, with accessory sulphide minerals, the marked areal coincidence of deeply extending veins, normal faulting, and igneous rocks, and the extreme differentiation of the parent magma as indicated by mica-peridotite dikes on the one hand and clastic silicic volcanic necks on the other hand, are the basis for postulating a magmatic origin for the fluorine. The sequence of chief significant phenomena is (1) doming and intrusion, (2) normal faulting, (3) mineralization, (4) post-mineral faulting. The writer believes that the ascending solutions originally carried fluorine, which readily hydrolyzed to form hydrofluoric acid, and this in turn reacted with calcareous wall rock materials and vein calcite to form calcium fluoride. In the Cave In Rock district, possibly an excess acidity at somewhat lower temperatures than in the more central parts of the field was responsible for the late deposition of marcasite rather than pyrite, in the fluorspar.[7]

For the fluorspar-barite-calcite veins of central Kentucky Johnston [7a] interprets low temperature origin rather than acidity of solutions on the basis of marcasite inclusions, because the central

[6] Lindgren, W.: Mineral Deposits. McGraw-Hill Publishing Co., p. 714, 1928

[7] Allen, Crenshaw, Johnston, and Larsen: Mineral sulphides of iron. Am. Jour. Sci., 4th ser., vol. 33, pp. 169–236. Buerger, M. J.: The pyrite-marcasite relation. Am. Mineralogist, vol. 19, no. 2., pp. 37–61.

[7a] Johnston, W. D., Jr.: Marcasite inclusions in fluorite from the central Kentucky barite-fluorite-calcite veins. Am. Mineralogist, vol. 11, no. 7, pp. 178–179, 1926.

Kentucky veins show little evidence of replacement. In the Cave In Rock deposits, however, solutions and replacement of the limestone were obviously dominant reactions.

The Cave In Rock Deposits.—The bedding replacement deposits clearly follow certain penetrable limestone beds beneath dense relatively impermeable or difficultly penetrable beds, and the larger bodies lie beneath the Rosiclare sandstone, which, only in the Cave In Rock district and immediate vicinity appears to have a shale base. From the forms, attitudes, and relationships to local minor structural features, the writer believes that the fluoriferous solutions ascended along a major fault zone, such as the Peters Creek zone, and thence followed a divergent and more or less fan-shaped system of minor faults and joints. Where the minor fractures reached only as high as a relatively dense stratum, or were greatly reduced in width upon reaching such beds, conditions were favorable for lateral spreading of the fluorine solutions and consequent strong reaction with the permeable calcareous host beds. Geographically, the dying out or restriction of minor fissures at certain horizons might be expected to occur particularly in the marginal belt of the regional dome. The presence of beds of different structural competency is also a factor. In the Cave In Rock district all these factors exist coincidentally. Bedding replacement deposits are rare and relatively small, so far as known, elsewhere in the extensive Illinois-Kentucky field, where pronounced normal faults provided relatively unimpeded paths for the ascending solutions. Such faults are lacking within the Cave In Rock district, though one such fault zone, the Peters Creek fault, borders it on the northwest.

Origin of the Banding.—The writer believes that the banding, textures, and relations to adjacent shale and limestone beds reflect and preserve the original bedding, cross-bedding, and to some extent the textures of the host limestone. Bastin,[8] on the contrary, believes that although there is a general parallelism between the banding of the deposits and the bedding of the country rock,

[8] Bastin, E. S.: The fluorspar deposits of Hardin and Pope Counties. *Op. cit.*, p. 53. Int. Geol. Congress Guidebook 2, *Op. cit.*, pp. 39–41.

the presence of divergences and characteristics of the banding argue for control of deposition by rhythmic precipitation from solutions that diffused through the replaced limestone from contacts and cross-cutting fractures. If this is true, the deposits become an outstanding example of diffusion banding. According to Bastin's theory the attitudes of the bands are not due to stratification features of the host rock, but are oriented normal to the direction of diffusion.

The writer was unable to discover evidence that any banding is parallel to cross-cutting feeding fissures except insofar as it may be attributed to simple fissure filling, and to be closely confined to the fissure zone. The angular attitude of some of the banding is, according to available data, entirely consistent with the type of cross-bedding known to characterize the Fredonia limestone member (Fig. 7), and the sets of such bands apparently are not persistently related to definite fissures. In one place at least, steeply inclined bands adjacent to a small fissure vein seem definitely to indicate preservation of drag in the wall rock. Moreover, the prevailing comb structure of the purer bands, the high fluorspar content of the " impure " bands, and, in places the alternation of bands of pure fluorspar with bands of quartz crystals, also showing comb structure, are considered inimical to the theory of rhythmic deposition, because of the monomineralic character of such precipitation, and the unidirectional nature of flow by diffusion.

The mechanism of simple diffusion of feeding solutions into the host rock material is not being brought into question. Undoubtedly such a phenomenon is a common process of impregnation by solution, where mineral bodies are formed by replacement. It is the significance of the banding as indicating rhythmic precipitation in successive bands—the Liesegang effect—that is debatable. Rhythmic precipitation has been assumed to require alternating conditions of supersaturation and under-saturation with respect to the precipitating material. Such conditions are readily conceivable in the classic example of the Leadville ores as

described by Loughlin,[9] but in the Cave In Rock deposits the precipitated substance, CaF_2 bears a base that was already highly concentrated in the host rock which was mostly $CaCO_3$. Deposition was not dependent upon access of Ca by diffusion from the source of supply through the extending body of solution for there was a great excess in the limestone. The experiments in Stansfield's paper [10] referred to by Bastin do not duplicate these conditions with respect to concentration. It is true that one of Hatschek's experiments, quoted by Stansfield, was the diffusion of a lead solution into gelatine containing both lead and potassium iodides, but even here the chemical concentration conditions are not exactly analogous to the fluorspar system. It was doubtless the potassium iodide that precipitated Hatschek's rings of lead iodide in this set-up. Conceivably, the presence of CaF_2 in the $CaCO_3$ (limestone) environment would not have prevented the formation of CaF_2 rings by diffusion of a fluoriferous solution.

For the formation and concentration of the fluorspar deposits the writer postulates ascending thermal fluoriferous solutions carrying hydrofluoric acid, and doubtless some calcium fluoride (a product of earlier reactions along the paths of access). Silicon tetrafluoride (SiF_4) may have been present also, but this compound, reacting with water and carbonates encountered along the paths of travel, would tend to precipitate quartz and to form CaF_2, according to the equations given below. The very slight content of quartz in most of the fluorspar bodies argues against the presence of much SiF_4 in the solutions at the horizon of the known deposits. On the other hand, SiO_2 formed as just suggested might theoretically be expected to occur in the zone of the main feeding fissures. Possibly the single belt of markedly silicious ore that appears to cut across Lead Hill and to follow part of the base of the escarpment argues for the existence of a prominent feeding fissure from which smaller divergent fissures radiate

[9] Emmons, S. F., Irving, J. D., and Loughlin, G. F.: Geology and ore deposits of the Leadville mining district, Colorado. U. S. Geol. Surv. Prof. Paper 148, pp. 202–204, 1927.

[10] Stansfield, J.: Retarded diffusion and rhythmic precipitation. Am. Jour. Sci., 4th ser., vol. 43, pp. 1–27, 1917.

to form the more localized channels of access to the sites of deposition of the exploited mineral bodies.

The following empirical equations, well known to laboratory chemists, are assumed to explain the reactions involved in the formation of fluorspar and quartz from the primary solutions:

(1) $2HF + CaCO_3 \rightarrow CaF_2 + H_2O + CO_2$.
(2) $4HF + SiO_2 \rightarrow SiF_4 + 2H_2O$.
(3) $3SiF_4 + 3H_2O \rightarrow H_2SiO_3 + 2H_2SiF_6$.
(4) $H_2SiF_6 + 3CaCO_3 \rightarrow 3CaF_2 + H_2O + 3CO_2 + SiO_2$.

In effect, equations (3) and (4) may be represented by the simpler equation:

(5) $SiF_4 + 2CaCO_3 \rightarrow 2CaF_2 + SiO_2 + 2CO_2$.

Comb Structure by "Replacement."—The formation of comb structure in closely spaced horizontal bands that may be traced in places for many feet demands special consideration, and the writer offers two hypotheses in explanation.

Reaching the horizon of the known fluorspar deposits by way of fracture systems and secondary faults, the solutions were impeded or deflected by the relatively impervious cap-rocks, at which beds the fissures terminated or were greatly restricted. The solutions spread laterally along the contact at the base of the cap-rock, with downward solution of the limestone and precipitation of fluorspar. Also, the solutions spread along bedding planes from the numerous cross-cutting fractures and lateral progressive solution of the limestone beds took place with almost immediate precipitation of fluorspar. Along the pure bands of the limestones a progressive solution cavity was thus formed, but concomitant precipitation of fluorspar occurred from the walls of the cavity toward the center. This reaction was stoichiometrical, according to the equation (1) quoted above. Continued precipitation of CaF_2, from solute already present in the migrating solutions,—derived of course by reactions at more distant points—nearly filled the cavities in continuation of the already formed comb structure. It is important to note that the stoichiometrical bal-

ance (equation 1) results in a decrease of volume, as the specific volume of CaF_2 is only about two-thirds that of $CaCO_3$. Fundamentally, this mode of deposition produced a true comb structure, rather than a pseudo-crustification, as suggested by Bain,[11] and earlier generalized by Emmons.[12]

An important conception in this hypothesis is that progressively-forming open spaces existed for a brief time along the pure limestone layers, as a result of the stoichiometrical volume change. In these spaces the solutions became saturated with calcium fluoride. Fluorspar was therefore precipitated upon the horizontal walls of the spaces, and the crystals grew as "combs" toward the center. An excess of calcium fluoride, transported from other points, permitted continued growth of the crystals, which, meeting in the central zone, gave support to the walls. Possibly this interpretation explains the apparent secondary growth of colored fluorspar in crystalline continuity with colorless fluorspar,—a common feature of bands and crystal-lined cavities.

The impure bands of the limestone, alternating with the pure bands, were subject to the same reactions, but the disseminated, non-reactive impurities acted essentially as a sponge-like or skeletal mass that prevented the development of comb structure. Spots and short streaks of coarsely crystalline fluorspar formed in the impure bands represent originally pure carbonate material in the impure limestone bands. Thus, by this method of replacement the bedding, cross bedding, and variations in degree of purity of the original sedimentary rock were faithfully preserved. Only the oolitic and fossiliferous beds, however, were sufficiently open-textured to allow this process to extend to any appreciable distance from the fissures, bedding planes, or contacts; the underlying or included beds of massive, dense limestone were only slightly affected.

A second and less favored hypothesis depends upon the relative permeability of the pure and impure limestone bands as promoted

[11] *Op. cit.*, p. 57.

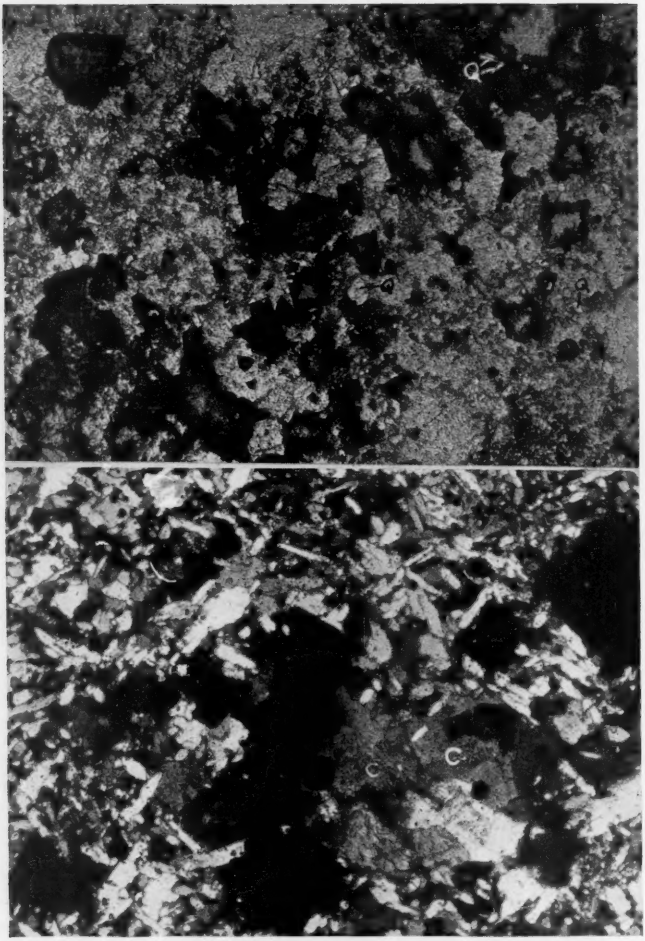
[12] Emmons, S. F.: Structural features of ore deposits. Am. Inst. Min. Eng. Trans., vol. 16, pp. 804–839, 1888.

by their porosities. The ferriferous carbonate of the impure bands (Fig. 9) was apparently less readily replaced by CaF_2. In some places at least these bands appear to be somewhat more porous, offering more space for the entrance and travel of fluoriferous solutions than the pure bands. Such impure bands may conceivably have acted as chief loci of access from which the fluoriferous solutions replaced the pure bands from each side toward the center. In this case the "comb" crystals would in large part represent true metasomes, and the excess calcium carbonate may well have been dissolved by the carbonated water resulting from the replacement reaction. It is pertinent to remark, however, that no central relics of limestone material have been seen in the pure fluorspar bands.

Schwerin in an excellent paper [13] has also attributed the voids of the pure bands as well as the larger crystal-lined solution cavities between the ore horizon and the shale cap-rock to the reduction of volume brought about by the replacement of limestone by fluorspar. His idea was a fundamental advance over earlier conceptions, and its rationality needs no further comment. The principle underlies the writer's theory of a stoichiometrical rather than a volume replacement, but Schwerin expressed only a part of the necessary process, for the contemporaneous filling of voids, rather than slumping between bands, seems a necessary concomitant to explain both the comb structure and the lack of structural distortion. Schwerin quotes from a private report by C. W. Greenland, who attributed reorganization of the silica impurity to the action of fluoriferous solutions. Greenland is thus in general agreement with the writer, who, however, believes that precipitation of quartz and replacement of $CaCO_3$ by CaF_2 were not separated by a time interval. The contemporaneity is indicated by the empirical equation 3 of the writer's earlier report,[14] and the succeeding inadequately expressed statement regarding its relation to some of the bedding deposits. The quotation from

[13] Schwerin, Martin: An unusual fluorspar deposit. Eng. and Min. Jour., vol. 126, no. 9, p. 336, 1928.

[14] Hardin County report, *Op. cit.*, p. 279.



FIGS. 9 AND 10.

Greenland's report also states that "the metasomatic nature is shown by the excellent preservation by the fluorite of the original granularity of the limestone. It is also evident that the original limestone was of varying composition, some being more siliceous and ferruginous than others."

Quartz Bands and Metasomes.—At a very few points along a nearly east-west zone crossing Lead Hill and the southernmost base of the "Spar Mountain" escarpment, bands of pure crystalline fluorspar alternate with bands of quartz crystals in comb structure, or with bands of completely silicified limestone.

The sub-Rosiclare stratum of calcareous sandstone is clearly made up of alternate bands of dominantly calcareous material and dominantly clastic quartz grains, the latter originally deposited as sand beds. The entire member is cross-bedded. The bands range in composition and texture from pure limestone, through sandy limestone, to slightly calcareous sandstone. Fluoriferous solutions penetrating such a mass might be expected to develop fluorspar in the calcareous bands according to equation (1) given above. The reactions represented by equations (2), (3) and (4) might be expected to prevail in the siliceous bands, with the ultimate production of recrystallized quartz from the clastic quartz grains of the original sediment, under the influence of the excess of $CaCO_3$, represented by original calcareous cement. The matted aggregate of quartz crystals displayed by thin sections of the very porous silicious bands thus indicate complete silicification of the calcareous bed, and the few sporadic micro-

FIG. 9. Photomicrograph (×35) of section from an "impure" band (Spar Mountain) showing unreplaced rhombs of ferriferous carbonate (dark) in ground-mass of fluorspar. The outer very dark zones of the carbonate grains are very limonitic. Numerous minute quartz crystals, some of which are indicated by *Q*, are also present.

FIG. 10. Photomicrograph (×35) of a siliceous band in material from dump of Cave In Rock mine, showing matted aggregate of small quartz crystals (light), larger irregular areas of quartz (gray), and fluorspar (black). Countless specks of carbonate are included in some of the larger quartz and fluorspar areas, as in vicinity of *C*. ×-nicols.

scopic crystals of quartz in some of the fluorspar bands suggest either recrystallization from impurities or introduction of silica from the solutions.

The recrystallization of quartz by the above process should be a common phenomenon in ore deposits formed from fluoriferous solutions in calcareous environments.

U. S. Geological Survey,
Washington, D. C.,
March 16, 1937.

A FAST AND THOROUGH METHOD FOR IMPREGNATING POROUS ROCKS.

R. VON HUENE.

THE purpose of impregnating a poorly cemented or porous rock before making a thin section, is to hold the particles of the rock together with balsam, where the natural bond is insufficient. In order to fulfill this purpose, the balsam of the impregnation should fill all pores completely, without leaving air pockets, and should be of the same hardness throughout the rock. The balsam should be neither too soft—since then it lacks the strength of holding the rock together and picks up abrasive in grinding—nor too hard—since then it is brittle and useless for its purpose.

In the usual method of cooking the rock in balsam, the balsam is generally too viscous to penetrate the rock to a considerable depth, and forms a cover on top of the rock which prevents the volatile matter in the interior from escaping. The result is that the pores are not completely filled with balsam and the contact between balsam and pore-walls is interrupted by air-bubbles; also that zones of different hardness of balsam exist in the rock, the balsam is too soft in the lower parts and picks up the abrasive in grinding, while the portion of the rock that is next to the slide glass may already contain over-cooked balsam which is useless for holding the rock together.

In the method described here, the rock is ground as nearly as possible to the dimensions of the slide and the surface which is to lie next to the slide glass receives as good a preparation as the rock will allow. After this preliminary preparation, the rock is allowed to dry thoroughly on the hot plate at about 120° C., and is then dipped into a solution of about 5 per cent balsam, dissolved in xylene. This thin solution readily enters the pores, and after the rock is returned to the hot plate, the xylene soon evaporates and leaves a thin coating of balsam along the walls of the pores.

As soon as the balsam on top of the section reaches the snapping point, this dipping is repeated, whereby the percentage of balsam may be gradually increased until the balsam forms a solid cover on top of the rock. As the balsam layer around the pore walls is thus gradually built up, it fills the pores completely and is of the same hardness throughout the rock. Artificial materials, such as soft wall-tiles, can be impregnated evenly to a thickness of ¼" in about 20 minutes. After this impregnation, the surface which was ground flat, is prepared carefully for mounting. Special attention should be given to rocks containing hard grains in a soft matrix, since due to the difference in hardness the soft particles may have been gouged out to a considerable depth in the rough grinding before the impregnation.

California Institute of Technology,
Pasadena, Cal.,
April 2, 1937.

DISCUSSION AND COMMUNICATIONS

HYDROTHERMAL LEACHING OF IRON ORES.

Sir.—Referring to Mr. John W. Gruner's article on *Hydrothermal Leaching of Iron Ores of the Lake Superior Type,* in ECONOMIC GEOLOGY, vol. 32, pages 121–130, Mr. Gruner may well be asked to point out the underlying intrusive rocks later in date than the Biwabic iron formation, whose upward-moving, gaseous emanations have, he claims, in co-operation with downward-moving surface waters, leached the iron formation of the Mesabi to form the ore bodies. The recent mapping for the preparation of Professional Paper 184 of the U. S. Geological Survey shows only Algoman and Archean igneous rocks underlying the Mesabi Range. Monograph LII of the U. S. Geological Survey shows Embarrass granite of Keweenawan age underlying the Mesabi Range from Trimble east, and from Mesabi east shows overlying Keweenawan gabbro. The existence of these later intrusives below and above the Mesabi Range coincides with the area in which commercial ore is not found. The iron formation throughout this area shows the typical mineral assemblage of contact metamorphism.

Westward of this area, these metamorphic minerals are not found, the later intrusives are not mapped as present, and commercial ores are found to exist.

If the commercial ores were formed in the iron formations by the action of rising hot gaseous emanations or solutions from intrusive rocks, such rocks must have been of subsequent date to the iron formations, and if such a condition exists it is hard to explain the strange unanimity with which all geological maps of the region fail to show any such intrusives higher or lower than the iron formation in the vicinity of the producing portion of the Mesabi Range.

Which underlying granite or greenstone is it that is younger than the iron formation and has sent out hot leaching solutions? Why does the conglomerate beneath the Pokegama quartzite contain samples of all of the underlying granites and greenstone, as described in Monographs LII and XLIII of the U. S. Geological Survey? Surely such potent mineralizers must have come from some traceable body of igneous rock; yet the only such underlying later igneous rock is coincident with the case-hardened, unproductive, metamorphosed east end of the range.

Referring to the discussion by the writer in ECONOMIC GEOLOGY, vol. 27, pages 487–491, and vol. 28, page 293, Mr. Gruner states that the writer " fails to mention that the ore body is intimately associated with a diabase dike upon which it is found." The Brotherton-Sunday Lake ore body rests upon Brotherton No. 1 dike, whose existence has always been known to all concerned since the earliest days of the mine, was mentioned by Mr. Gruner in his article which this writer was discussing, and was therefore not mentioned by this writer in the discussion because there was no disagreement as to its existence.

Mr. Gruner, in his article which was discussed by the writer (ECONOMIC GEOLOGY, vol. 27, pages 189–205), made the statement that the conformable overlying slate in the hangingwall of the iron formation had never been removed by subsequent erosion except at one point in the Brotherton-Sunday Lake region, and at this point he stated that no evidence of concentration on the subsequent erosion surface had been found. The writer's discussion was to point out that such evidence had been found right there, in the form of a pre-Keweenawan river channel which had bitten deeply into the Huronian iron formation, and that concentration along this river channel was found. This concentration extends far above the dike which is the carrier of the Brotherton-Sunday Lake ore body, and is found, at that horizon, only in the vicinity of the ancient river channel at the base of the Keweenawan. Ore pebbles in this river channel indicate that concentration existed before the Keweenawan lavas poured out. That this

river channel concentration was not related to the dike is rather clear, because there is evidence in the immediate neighborhood that the eastward-pitching Gogebic dikes intrude the lower Keweenawan lava flows. It is not known that all of the Gogebic dikes so intrude the Keweenawan but it is known that a number, if not most of them do. Incidentally the Brotherton-Sunday Lake dike mentioned by Mr. Gruner is diorite and not diabase as he describes it.

Where are the sinters produced by the surface out-pouring of the hot solutions? Are there remnants of them and of the quartz veins that must have led to them? If not, why not?

Mr. Gruner has made no answer to the objection which has been raised that all of the places where subsequent igneous action has had the best chance to work on the iron formation of the Mesabi and Gogebic ranges are places where ore bodies, instead of forming a bonanza, are totally absent.

Mr. Gruner does not mention in his denial of surface weathering as an origin of ore on either ancient or current land surfaces, the extensive ancient erosion surface at the base of the Goodrich quartzite on the Marquette Range, with its remarkable accompaniment of hard ore bodies definitely referable to that erosion cycle.

In the classic instances of the action of igneous solutions, such as the great ore deposits of the Cordillieran region of the west, the magmatic source of the emanations is a concrete occurrence with important areal development and definitely known intrusive relationship to the strata in which the ore deposits are located. On the other hand, in the Lake Superior region, wherever similar intrusive relationships are clearly in evidence, subsequent ore bodies are missing and the formation is rendered wholly unamenable to the concentration of ore. The only ore bodies in the Lake Superior region that are found in the neighborhood of igneous intrusion of later date than the iron formation are definitely referable to erosion cycles that affected the iron formation before the subsequent intrusion took place. In all these cases hard ores

have resulted, which give every evidence of having been caused by the action of later igneous agencies and/or diastrophism on pre-existing soft ores.

Speculation may be an important source of new knowledge and ideas, but it remains pure speculation unless it can be harmonized with field evidence.

CRYSTAL FALLS, MICH.,
April 2, 1937.

STEPHEN ROYCE.

REVIEWS

Naphthenic and Paraffinic Oils. Their Geologic Distribution and Origin (Naphthen = Und Methanöle Ihre Geologische Verbreitung Und Entstehung). By HANS HLAUSCHEK. 11 in O. Stutzer's series: Schriften aus dem Gebiete der Brennstoff-Geologie, Ferdinand Enke, Stuttgart, 1937. Pp. 147, figs. 14: 15 RM. (less 25 per cent. for sales to most countries outside Germany); in German.

The book is built around the study of extensive series of analyses of Polish and Roumanian crude oils but extends to a brief survey of the relative conditions of occurrence of naphthenic and paraffine base crudes throughout the world. The findings of fact are: (1) Character of the oil and age of the reservoir rock: Paraffinic oils are the predominant oils in Paleozoic rocks; and they and the intermediate base oils occur in rocks of all ages from Silurian (Ordovician ≡ Lower Silurian) to late Tertiary; the naphthenic oils are the predominant oils in Tertiary rocks but are found in rocks as old as Lower Cretaceous; this relation is strikingly true of North America, and true in a general way of the world as a whole; (2) Character of the oil and depth of the reservoir rocks: No general relation holds between character of oil and depth but within individual oil areas, most commonly the oil becomes lighter with depth; (3) Character of the oil and tectonics: No relation was found between tectonics and the character of the base of the crude oil. (Note: No consideration is given to the problem of the character of the oil and carbon ratio ≡ metamorphism); (4) Character of the oil and character of the reservoir rock: No relation was found. Having made an interesting review of the theories of the formation of oil, the author comes to the final conclusion:

(*a*) The theories which postulate that oil may form at low temperature and pressure and therefore at moderate as well as great depth, have a greater degree of probability than those which depend on the postulate of the formation of oil as paraffinic oil, at great depth; (*b*) The various chemical characters of different crude oils seem most probably to have depended, in the main, upon differences in the character of the mother material; and (*c*) Once an oil is formed its character changes only slightly; (*d*) For the Carpathian oil provinces, in general the source beds and reservoir beds probably lie in the same or adjacent formations; the postulation of the origin of the Dacic and Meotic oils from a common

mother rock seemingly should be given up; the oil in the Dacic (third oldest Pliocene formation) formed in post-Meotic beds (Meotic ≡ oldest Pliocene formation); the Meotic oil in Meotic beds, or—less probably—in Miocene beds; most of the Flysch oil in the Flysch—contrary to the common teaching that the Flysch is barren of oil; and the late Tertiary oil of the Vienna basin in the late Tertiary beds.

This book presents an interesting original study of the Carpathian oils, an interesting review of the occurrence of the paraffinic and naphthenic oils throughout the world, a clear formulation of the theories of the relative manner of the formation of naphthenic and paraffinic oils, and conclusions with half of which the reviewer agrees and with half of which he disagrees. The book is well written and readable, the thread of thought is easy to follow, and the German is simple. The book is recommended to students of the subject of the origin and evolution of crude oils.

Three mutually dependent conclusions of the author do not seem to the reviewer to be justified: (*a*) That the present character of a crude oil depends, in the main, upon the character of the assemblage of mother material; (*b*) that in general after an oil has been formed, its character undergoes no substantial transformation; and (*c*) that naphthenic crude oils have not transformed into paraffinic oils under the effect of temperature, pressure, time, and other factors.

The question of the degree to which the character of crude oil depends upon the character of the original source material seems to the reviewer one about which the data are insufficient for final conclusion. Variations in the assemblage of organic mother material of crude oil seemingly must produce some sort of parallel variation in the resultant crude oil. The vast change in the forms of animal and plant life, particularly the latter, from Ordovician to Pliocene seemingly should be parallelled by some change in the character of the crude oil. Accordingly the theory that the Paleozoic assemblages of organic mother material of petroleum were such as to give rise to paraffinic rather than naphthenic crude oil must be held for the present as an important alternative explanation of the practical absence of naphthenic petroleum from Paleozoic rocks. In view of the very great lengths of geologic time since the end of the Paleozoic compared to those since the Eocene, however, the theory that paraffinic base is the asymptotic end point of evolutionary transformation of the base from naphthenic is an equally good alternative explanation of the character of the Paleozoic oils.

The theses that paraffinic oil cannot form from naphthenic and that the character of an oil is relatively stable after the oil has once formed seem to the reviewer inconsistent with the fact of the general decrease with depths of the specific gravity (increase of A.P.I. gravity) of the individual 25° C. cuts in the U. S. Bureau of Mines analyses for Gulf Coast oils of each of the age groups: Miocene, Oligocene, and Jackson Eocene.

The special counter plea might be made that in general, the depth of sinking increases linearly gulfward and that the apparent variation of character with present depth is the effect of the original shoreward variation in the character of the assemblage of mother material of the crude oil. In a study now in progress, a criterion has been found which seemingly allows the recognition of some crude oils of common assemblage of source material; decrease of specific gravity of the distillation fractions with depth is shown by these groups and therefore, leaves no opening for that special plea. The ease with which the character of crude oil is changed in the refinery suggests to the reviewer the high probability of parallel changes in nature, presumably at very slow rates, but changes which are appreciable on account of the great lengths of geologic time.

DONALD C. BARTON.

HOUSTON, TEXAS.

Geologie von Asien. By KURT LEUCHS. Bd. I. Teil. 2 (Schluss). Pp. viii + 317. Figs. 145. Gebrüder Borntraeger, Berlin, 1937. Price (paper), 24.40 RM.

The second part of Volume I of the Geology of Asia (see this JOURNAL, Vol. XXX, page 709) deals with the central part of the Continent, extending from the Caspian Sea to the mountains on the east border of Mongolia, and from the south side of the Himalaya Mountains to the fault zone in Middle Siberia in the latitude of Lake Baikal.

It describes in as great detail as is to be expected the physiography, stratigraphy and tectonics of the region, which is divided for this purpose into large structural blocks, as for instance, Mongolia, Tianschan, the Pamir district and Tibet, including the Himalaya Mountains and the Tarim Basin. In each area structure is emphasized, but a general statement of its stratigraphy is given and a very brief account of its physiography. There is very little in the description that is new, but the literature on the area is so scattered that it is very difficult of access to most geologists. The value of the book is that here for the first time this scattered literature is brought together in one place. In the bibliography are listed about 225 articles, many of which are in Russian.

Near the close of the book are 11 pages summarizing the little that is known of the mineral resources of the area.

W. S. BAYLEY.

An Attempt at the Correlation of the Ancient Schistose Formations of Peninsular India. By L. L. FERMOR. Mem. Geol. Survey India, Vol. 70, Part 2, No. 1, pp. 53–217 (1936).

In Part I of this memoir, recently reviewed here, Sir Lewis Fermor divided the Archæan of India into regions and provinces for purposes

of description. No. 1 of Part 2, describes three of these provinces—the Dharwar-Mysore-Nellore province, the Chanda-Bastar Province and the Singhbhun-Orissa province.

The Dharwar-Mysore-Nellore Province.—This province contains the so-called "classic ground in which Foote originally separated the Dharwar formation from the associated gneisses." Sir Lewis treats us to a fine summary of the work that has been written on the non-charnockite areas of South India, and lucidly traces the oscillations in viewpoint and understanding of successive geologists who have worked on these rocks.

Newbold's earliest view (1844) that the granitic rocks had intruded earlier schists and gneisses, was largely accurate and it is curious that over 60 years elapsed before this view became accepted. It is a fine illustration of how scientific advancement is so often held up by blind belief in a popular view.

R. B. Foote's first descriptive work on the South Indian rocks appeared in 1876, but it was not until 1886 that he proposed the term "Dharwar" for the schistose rocks that occur as wide bands in the "granitoid gneisses," and later described eight such bands. He refers to the Dharwar system as "Lower Transition," and, rejecting Newbold's views of the intrusive relation of the gneisses into the schists, concluded that the Dharwar rocks rested unconformably on the granite-gneisses.

J. Malcolm Maclaren, who worked in this part of India for a very short time at the beginning of this century, continued to believe in this stratigraphic unconformity between the Dharwars and granite-gneiss. Maclaren did no detailed mapping yet he drew comparisons between these Dharwars and the rocks in Chota Nagpur, Rajputana and even Behar and Shillong. Maclaren's work in the economic field was invaluable, but I feel that this correlation was the one unfortunate contribution that Maclaren made to Indian geology. The term "Dharwar" should not have been given such a wide significance in Indian geology at that stage, as the comparisons were not based on mapping but on mere generalized lithological resemblances. Its use has given a bias or color to all subsequent work in these areas, which should never have been present.

Then followed the work of the Mysore Geological Department of which Foote was the founder. No comprehensive account of this part of India has appeared since Smeeth's outline in 1916. The Dharwars are divided into an upper (chloritic) and a lower (hornblendic) division without any break between the two, and the whole intruded by a succession of granites and basic igneous rocks, the Dharwars being recognized as the oldest rocks present. Smeeth, in 1926, concluded that the "lower division" is intrusive into the "upper," a view which Jayaram later rejected. A calcareous and manganiferous division has also been recently recognized, and known as the "Sakarsanhalli series" which may be a

still lower division. Of the intrusive granites the Peninsular gneiss is the most widespread.

The various opinions as to whether the quartzites, ferruginous quartzites, limestones and schists are of sedimentary origin or are due to replacement of igneous rocks, are stated fairly enough by Sir Lewis, as also is the controversy concerning the sedimentary or crush origin of certain conglomerates. Notwithstanding that Sir Lewis refuses "to accept any conglomerate in the Archæan as truly sedimentary except on the most rigid proof," an attitude which he so strongly assumes in Part I, it is good to read that he does acknowledge the recent views of Rama Rao and Pichamuthu that sedimentary conglomerates actually occur. His criticism of Iyengar's, Smeeth's and Jayaram's inclusion of the intrusive Champion gneiss as part of the Dharwar system is justifiable.

Rama Rao and Jayaram were the first of recent writers to reject the view of Smeeth an Iyengar that all the Dharwars are of igneous origin, and they accept a sedimentary origin for many of these rocks. Sir Lewis' review of this work in South India leaves an impression that needless, weak and illogical arguments were the burden of past descriptions, and that a little acknowledgment of simple views and analogies from other areas would have cleared the air. It is all expressed so concisely by one small phrase in the memoir "After all, the Sakarsanhalli rocks are mainly shreds"—the same might be said of all these schist belts of South India as compared with the Archæan tracts in other parts of the country. This, indeed, is one of the reasons why I believe that the Dharwars have been given a position as a type system in our Indian stratigraphy out of all proportion to their importance. Those who have worked long in India will read this historical account with a certain feeling of regret, perhaps, that Sir Lewis has found it necessary to take out some of our skeletons once more for an airing.

Chanda-Bastar Province.—This extends north from the Godavari river and three-quarters of it lie in the Central Provinces. It is bounded on the east roughly by the Eastern Ghats and on the west by the Deccan Traps, Gondwanas and Puranas. Little has been published concerning this tract during recent years, and the last memoir of any importance appeared in 1902—Sir Lewis refers to Smith's account of the Raipur and Sambalpur districts, dated 1899, as "fairly modern"! Amongst other faulting Sir Lewis deduces evidence for a fault zone some 600 miles in length, which threw down the Chanda-Bastar province several thousand feet relative to the adjacent Eastern Ghats province.

During the last few years Geological Survey of India parties have been engaged in the Bhandra district of this province under the supervision, until recently, of Sir Lewis. Here, the Sakoli series is regarded as younger than the Sausar series which crops out to the north. A sur-

vey of Bastar State, in the eastern part of this province, has recently been commenced by Mr. H. Crookshank and Dr. P. K. Ghosh. There, a series of metamorphosed sediments have been intruded by granitic rocks; ferruginous quartzites form an important part of the series. Summarizing the features of the Chanda-Bastar province Sir Lewis notes that the phyllites, schistose rocks and gneisses are more or less parallel to the general north-south trend of the rocks in the Dharwar-Mysore-Nellore province. The phyllite-schist suite has received different names in different areas: Sakoli series in Bhandara, Chilpi Ghat series in Balaghat and Drug, and Sonakhan series in Bilaspur, Raipur and Sambalpur. All are compared with the Dharwars of South India. The chief rocks are slates, phyllites, mica-schists, chloritic and hornblendic schists, quartzites and hematite-quartz-schists. Calcareous rocks are entirely absent.

The province is large and the schists are widely separated in the granite-gneiss. So little is known, apart from the Sakoli and Sausar series, that there is no justification for any correlation as yet between areas.

The Singhbhum-Orissa Province.—We come next to the area which has been my own hunting ground during the last 15 years. It is a small province, but it will be interesting to see later the reason for the separation of the Ranchi and Bihar provinces which lie to the north, and which in actual fact form a very definite unit with Singhbhum geology. Economically it is the most important mineral tract in India.

Sir Lewis summarizes the early work of Haughton, Stoehr, Ball, Maclaren and Fermor in Singhbhum and surrounding areas; of these Ball alone did any extensive mapping, but Fermor mapped about 20 square miles around some chromite deposits. The early views were more or less parallel to those expressed for South India, except that at no time was such a wholesale relation of schists to an igneous origin postulated. Ball's memoir (1881), the result of reconnaissance work of a most erudite type, was the most momentous, but to a modern reader it suffers from inhibitions attendant on the geological beliefs of those days.

An important omission is the work of K. A. K. Hallowes in 1905–1908, whose progress reports were available to Sir Lewis. He was the first to point out the intrusive nature of the granites into the schists, and there is much valuable information buried in Hallowes' reports.

A good account is given of the more modern detailed surveys, which have covered approximately 10,000 square miles since 1920. The three principal workers, Jones, Dunn and Krishnan, receive a good hearing, with also a mention of Dey's work; I should have liked to have seen some reference to the work of other colleagues, for example, of Hobson and Iyer who have done some useful mapping in this area. This work has been described recently in several memoirs and others will appear

shortly. But even so, I feel that our conclusions are unsatisfactory. Almost at the beginning Jones found that wonderful section along the Deo river, where the basal bed of the Iron-ore series rests on the vertical beds of an older metamorphic system—in no country have I seen exposed so clear a section of the unconformity between two Archæan systems. Almost from the beginning, therefore, we were aware that two systems of rocks were present: indeed my own field work in India commenced from the actual site of this Deo river section. In Singhbhum and surrounding areas is the following succession:

Iron-ore series
7. Dalma lavas, with agglomerates and phyllites.
6. Dhanjori quartzites (with occasional conglomerates)—impersistent.
5. Phyllites with tuffs, lavas, limestones, conglomerates, quartzites.
4. Banded hematite quartzite.
3. Shales, phyllites, mica schists.
2. Limestones—impersistent.
1. Basal sandstone—conglomerate.

Older Metamorphic system.

The Older Metamorphic system does not cover a wide area, but wherever found its rocks are litholigically similar to the metamorphosed types of the younger Iron-ore series. Although no banded hematite-quartzites and iron-ores have as yet been found in the older group, the fact that pebbles of these ferruginous rocks occur in the basal conglomerate of the Iron-ore series indicates that such iron-ore rocks were present in the Older Metamorphic system. Lithologically the older system resembles the Dharwars of South India just as much as does the Iron-ore series.

The Iron-ore series should be regarded as a *system*, but it is the policy of the Geological Survey to retain the term *series* until correlations between widely separated areas have been effected. The unconformity between the Older Metamorphic system and the Iron-ore series represents a vast period of time, but in the Iron-ore series itself there are overlaps and erosion intervals permitting a grouping of the beds into stages. Going downwards in the system there was an erosion interval immediately preceding the Dalma lavas, a very considerable erosion interval preceded the Dhanjori quartzite and conglomerate, brief intervals occurred in the underlying stage of tuffs etc., and finally, in South Singhbhum and Keonjhar, such a prolonged period of erosion preceded the banded hematite-quartzite that almost the whole of the underlying shales was removed and the Iron-ore beds occupy almost a basal position.

Sir Lewis discusses the outcrop of basal conglomerate immediately around the Deo river section as if it were a problem. There is no

problem to those of us who have followed this bed along the strike—I personally have mapped it for over 30 miles where it is found continuously between the granite and overlying shales and limestones. There is, however, a problem in regard to the adjacent Singhbhum granite. Most of this granite is definitely intrusive into the Iron-ore series, but I am of the opinion that some of the granite intrusive into the Older Metamorphic system is older than the Iron-ore series. Most of Sir Lewis' difficulties arise from the fact that his acquaintance with the geology of this area is based largely on a traverse of the copper belt and on a few brief visits.

Continuing these surveys to the west, in Gangpur State, Dr. Krishnan has recently found a suite of calcareous rocks which he calls the Gangpur series, and which he believes is older than the Iron-ore series, but younger than the Older Metamorphic system. Recognizing the several erosion intervals within the Iron-ore series, some of which have been very prolonged, and having surveyed the country up to the border of Krishnan's area, it seems to me possible that the Gangpur series may represent a stage (not necessarily basal) of the Iron-ore series (or system) elsewhere removed. However, discussion of this may preferably be left until Krishnan's memoir appears and his evidence can be more fully appreciated. Sir Lewis Fermor would correlate the Gangpur series with the Sausar series of the Central Provinces—still, 350 miles separate the two areas and correlation at this stage seems to be mere speculation.

Fermor remarks that in 1929 I discussed the possibility of correlating the Singhbhum rocks with the Dharwars of South India, following my predecessors. I no longer do so, however, for I regard such correlation as premature. Sir Lewis commences by accepting them as Dharwars, then sets out to prove his correlation.

At the end of each chapter the features of the province described are summarized and the lithological resemblances are indicated on which a correlation with other areas may be suggested. These lithological grounds reach a maximum for the Singhbhum-Orissa province. They include such rocks as iron-ore deposits, hornblende-schists, aluminous rocks, manganiferous rocks, calcareous rocks, carbon-phyllites, ultrabasic rocks, and granophyres. Of the iron-ore deposits similar rocks must have occurred in the Older Metamorphic system, as also do hornblende and other schists, and ultrabasic rocks. Of the manganiferous rocks we have at least two horizons in the Iron-ore series, either of which could have given rise to gonditic types under suitable metamorphism, and there are also the manganese deposits in the Gangpur series. Calcareous rocks are present in the Iron-ore series, in places thick but nonpersistent in this area—it is easy to visualize their swelling to the proportions known in the Gangpur series. Carbon phyllites are present in both Iron-ore and Gangpur series; it is not correct to say they are less important in the

Iron-ore series, as Sir Lewis believes. As to the intrusive granophyres, from pebbles in the Iron-ore series there was a pre Iron-ore granophyre, another is intrusive into the Iron-ore series and yet a third is an acid differentiate of the much later Newer Dolerites—microscopically identical with each other. These rocks provide no reliable evidence and I, personally, cannot accept any correlation on lithological grounds. To geologists not familiar with our Indian Archæan geology there is the possibility that resemblances marshalled in this way may appear to masquerade under the guise of logical premises. Time after time colleagues working with me in my area or in other areas have discussed with me these lithological similarities to the Iron-ore series rocks, but in recent years I have believed it wiser to put a brake on this type of correlation, and await the accumulation of evidence which will form a more logical basis. The field of comparative stratigraphic succession should prove a valuable aid, however, and there are signs of its ultimate use in Fermor's account.

It appears that Fermor's correlation, so far as his account has gone, is approaching lines similar to those which have suggested themselves to his colleagues, but which they have hesitated as yet to pursue.

In this review I have found it a little difficult to sift the principal features from the mass of detail irrevelant to the object of the memoir. Furthermore Sir Lewis has not always accurately recorded my less important views and I rather suspect the same on other minor points. I should like to have seen extracts taken from individual worker's own memoirs wherever possible rather than from General Reports; this particularly applies to the memoir of H. C. Jones which was in Sir Lewis' hands some three or four years ago.

J. A. Dunn.

Geological Survey of India,
Calcutta, India.

Mineral Resources of South Africa. Pp. 454. Geol. Survey, Pretoria, 1936. Price 1/–.

A valuable summary of the geology and occurrence of the many mineral deposits of the Union. Section 1 deals with the geology and topography and includes a review of the mineral industry. Section 2, Precious Metals and Minerals, deals with the history, geology, economics and industry of the diamond, of other precious minerals and of gold, platinum and silver. Section 3 deals with 23 base metallic minerals; and Section 4 with 22 non-metallic products. Section 5 takes up the economic minerals of Southwest Africa and Section 6 is statistical tables. The book resembles a textbook of mineral deposits and is a valuable reference for

anyone who desires information regarding mineral occurrences and industries of the Union. It is concisely written and is a tribute to the careful work of the staff of the Geological Survey.

ALAN BATEMAN.

Our Natural Resources and their Conservation. A. E. PARKINS AND J. R. WHITAKER, Editors. Pp. 650. Wiley & Sons, New York, 1936 (November). Price $4.00.

This volume represents the contributions of 22 authors well known in their respective fields. It covers the broad field of conservation as is set forth in the opening chapter by Wallace W. Atwood. It deals with conservation of the public domain, soils, erosion, arid lands, overflow lands, grasslands, tree crops, forests, water supply, minerals, fuels, wildlife, recreational resources, and even of man. Of particular interest to geologists are Chap. 3, Soils of the U. S., by L. A. Wolfanger; Chap. 4, Soil Erosion and its Prevention, by H. H. Bennett; Chap. 6, Arid and Semi Arid Lands, by R. H. Brown; Chap. 12, Water Supply for Domestic and Industrial Uses, by R. M. Brown; Chap. 15, Floods and Flood Control, by Guy-Harold Smith; Chap. 16, Our Mineral Treasures, by W. H. Haas; Chap. 17, The Mineral Fuels, by N. A. Bengtson.

The book contains much of value for geographers and general geologists.

Introduction to Theoretical Seismology. By J. B. MACELWANE AND F. W. SOHON. Part I, Geodynamics, by J. B. Macelwane. Pp. 366, figs. 67. Wiley & Sons, New York, 1936 (November). Price $6.00.

This is a book for the specialist. The geologist will flounder in a mass of higher mathematics between pages 10 and 227. If he can read it he will feel well introduced to the subject. He will, however, find something of interest in the last three chapters on Interpretation of Seismograms, Determination of Epicenters, and Depth of Locus.

Geography of Latin America. By F. A. CARLSON. Pp. 642; figs. 200. Prentice-Hall, New York, 1936. Price $5.00.

A carefully written, well illustrated geography that takes up the history, physical features, people, culture, health, transportation, agriculture, industries, trade, and mineral resources of each of the Latin American countries. It is enjoyable to read, informative, is a good text, and is valuable to those interested in Latin American culture, trade and mining.

BOOKS RECEIVED.

J. D. BATEMAN.

Natural Bonded Moulding Sands of Canada. C. H. FREEMAN. Pp. 144, figs. 7, pls. 11. Can. Dept. of Mines, Mines Branch, No. 767, 1936. Price, 25 cts.

Droughts of 1930–34. J. C. HOYT. Pp. 106, figs. 69, pls. 1. U. S. Geol. Surv., W–S. P. 680, 1936. Price, 20 cts. Causes of droughts, effect on ground and surface water, damage and relief.

Mining Industry of Yukon, 1935. H. S. BOSTOCK. Pp. 12, Can. Dept. of Mines, Geol. Surv., Mem. 193, 1936. Price, 10 cts. Placer and lode gold, silver-lead and copper.

Geology and Mineral Deposits, B. C. Nickel Mines, Yale District, B. C. H. C. HORWOOD. Pp. 15, map. Can. Dept. of Mines, Geol. Surv., Mem. 190, 1936. Price, 10 cts. Late Paleozoic to late Mesozoic.

Mineral Deposits in Renfrew County and Vicinity, Ont. B. C. FREEMAN. Pp. 34, fig. 1. Can. Dept. of Mines, Geol. Surv., Mem. 195, 1936. Price, 25 cts. Lead-zinc, molybdenite, graphite, feldspar, nepheline, beryl, gold, platinum, copper, nickel and mica in pre-Cambrian and Paleozoic.

The Thiem Method for Determining Permeability of Water-Bearing Materials. L. K. WENZEL. Pp. 57, figs. 7, pls. 6. U. S. Geol. Surv., W–S. P. 679-A, 1936. Price, 10 cts. Thiem method is applicable to conditions found in nature with modified procedure for computing coefficient of permeability.

Carmacks District, Yukon. H. S. BOSTOCK. Pp. 67, fig. 1, pls. 3, map. Can. Dept. of Mines, Geol. Surv., Mem. 189, 1936. Price, 25 cts. Lode and placer gold, silver, lead, zinc, copper, antimony and bituminous coal.

Platinum and Allied Metals (2nd Ed.) Pp. 137. Imperial Inst., London, 1936. Price, 3/-. Occurrence, mining, concentration, extraction and refining; world's resources, production, marketing and description of deposits; Canada leads in world production while platinum is Abyssinia's chief metal product. An interesting and informative publication.

Oil and Gas Map of New Mexico. D. E. WINCHESTER, revised by A. ANDREAS. State Bureau of Mines & Mineral Resources. (New Mexico) 1936. Price 75 cts. paper; $1.25 mounted. Revision on scale of 1 to 1,000,000: contains locations of axes of about 200 anticlines, 1200 wildcat wells with depths and results obtained, and main gas and oil pipe lines, refineries and natural gasoline plants.

Fifteenth Annual Report of the Secretary for Mines for 1935, and the twenty-eighth Annual Report of H. M. Chief Inspector of Mines for 1935. H. M. Stationery Office, London. 1936. Price $1.10. An account of the progress of the mineral industries of Great Britain during 1935. Largely statistical.

Geology and Fuel Resources of the Southern Part of the San Juan Basin, New Mexico. Part 2. The Mount Taylor Coal Field. C. B. Hunt. Pp. 49, pls. 8, figs. 2, maps 6. U. S. Geol. Surv. Bull. 860–B, 1936. Price, $1.00. Description of narrow subbituminous coal beds.

Geology of the Iramba Plateau, Tanganyika. N. W. EADES. Pp 35, map. Dept. of Lands and Mines, Tanganyika, 1936. Price, 2/6. Geomorphology, structure and petrography with descriptions of gold mines and prospects.

Annual Report, 1935. Department of Lands and Mines, Tanganyika Territory, 1936. Pp. 43, plate. Price, 1/6. Geol. mapping, gold, wolframite, galena phosphate, coal, and groundwater.

Gold Occurrences of Ontario East of Lake Superior. E. D. KINDLE. Pp. 167, index map. Canada Dept. of Mines, Geol. Surv. Mem. 192, 1936. Price, 50 cts. Brief review of all mines, prospects and important gold discoveries in thirty-two map areas, including Porcupine and Kirkland Lake as well as more recent discoveries.

General Alphabetical and Analytical Index of Publications of Amer. Inst. of Min. and Metal. Engineers, for 1926 to 1935. Pp. 431. Published by the Institute, New York, 1936. Price, $7.00. This covers volumes 73–117, unnumbered volumes, and special volumes.

Roemer's Texas. 1845 to 1847. Translated by OSWALD MUELLER. Pp. 301. Standard Printing Co., San Antonio, Texas, 1935. An account of Ferdinand Von Roemer's early geological exploration in Texas. A unique bit of writing; an example of careful observations and geological reasoning, and of delightful travelogues of the early colorful history of the state.

SCIENTIFIC NOTES AND NEWS

N. L. BOWEN will resign from the Geophysical Laboratory at Washington to succeed Professor Johannsen as Professor of Petrology at the University of Chicago.

FREDERICK G. CLAPP spent the greater part of 1936 in the Near East of Western Asia, making many exploration trips, one beyond the Hindu Kush range of northern Afghanistan. Explorations in Iran were continued. There is no change in his address.

D. F. HEWETT addressed the Geological Club at Yale University on April 16 on the Origin and Environment of the Hypogene Manganese Minerals.

J. A. DUNN, of Calcutta, India, has been nominated Associate Editor of the journal of ECONOMIC GEOLOGY to succeed L. L. Fermor, retired.

C. S. CULLIS has been selected as the next president of the Institution of Mining and Metallurgy (London).

C. W. WRIGHT, foreign mineral specialist for the U. S. Bureau of Mines, will spend the next few months in the Balkan States. General surveys of the mineral industries in Italy, Germany, Poland, and Czechoslovakia were completed in 1936.

E. N. PENNEBAKER, chief geologist for Consolidated Copper Mines Corp., has returned to Kimberley, Nev., from Warren, Ariz., where he has been carrying on special areal structural geological mapping.

S. J. SHAND, of the University of Stellenbosch, South Africa, has been appointed Professor of Geology at Columbia University. Professor Shand, who will conduct the courses in petrology, will arrive at the University in September.

CHARLES P. BERKEY was given a testimonial dinner on his seventieth birthday, March 25, at the Hotel Astor, New York City. There were 274 people present and more than 600 letters and messages of congratulation from friends who could not attend.

EARL B. NOBLE, formerly assistant manager of exploration of the Union Oil Company, has been appointed chief geologist, and Harold Hoots has been appointed assistant chief geologist, with offices in Los Angeles, California.

PAUL ARMSTRONG, having concluded his work in Nova Scotia for the Geological Survey of Canada, has reopened his office at 223 Drummond Bldg., Montreal, as consulting geologist specializing in structural ore problems.

C. H. BEHRE is planning to attend the International Geological Congress in Russia this summer and then to spend a few months investigating certain features of zinc-lead deposits in Europe.

LEONARD B. RILEY is now geologist for the London Gold Mining Co., located at Fairplay, Colo.

W. P. ALDERSON is leaving Kenya Colony on April 23 to return to Montreal via New York.

MAX W. BALL is now associated with Abasand Oils, Ltd., with head-

quarters at Edmonton, Alta., where the executive offices of the company have been moved from Toronto.

K. D. WHITE, petroleum geologist, has moved his office from London to Bucharest, Rumania, where he may be addressed, Bulevardul Tache Ionescu, I.

HANS STILLE, of the Geological Institute, University of Berlin, has been elected an honorary member of the American Association of Petroleum Geologists.

W. R. WADE, formerly associated with the late Hon. John Hays Hammond, has announced the opening of offices as consulting mining engineer and geologist at 315 Montgomery St., San Francisco, California.

PAUL BILLINGSLEY, consulting mining geologist, is permanently located at Still Waters, Burton, Wash. On March 18 he addressed the Utah Chapter of the A. I. M. E. at Salt Lake City on the progress of gold mining at Goldfield, Nev.

NED E. NELSON has been appointed consulting geologist to the Britannia Mining and Smelting Co., Britannia Beach, B. C.

KENNETH LEITH, mining engineer and geologist, of Amherst, Va., and Washington, D. C., recently went to Costa Rica on a short professional trip.

AUGUSTUS LOCKE, consulting geologist, has resigned his position with the Eastern Exploration Co., Goldfield, Nev., and has resumed consulting work in British Columbia.

MR. FRANK EBBUTT has moved from Britannia Beach, B. C., to 173 Glenrose Ave., Toronto, from where he will carry on geological investigations in eastern Canada for the Howe Sound Company.

CLAYTON G. BALL, geologist and coal technologist formerly with the State Geological Survey of Illinois and more recently with the Bell and Zoller Coal Company, has become associated with Paul Weir, consulting mining engineer, 307 North Michigan Ave., Chicago.

E. LEITZ, INC., has announced the removal of its headquarters in New York from 60 East Tenth Street to the Hockscher Building, 730 Fifth Avenue.

C. H. SMYTH, JR., emeritus Professor of Geology at Princeton, died April 4 at Princeton, from pneumonia and complications resulting from a fractured hip received in a fall two weeks previously. He was 71 years old. He was a member of the Hamilton College faculty for 14 years and of the Princeton faculty for 29 years. His major scientific contributions related to the Clinton iron ores, the regional geology and mineral deposits of the northwest Adirondacks, the origin of alkali-rich igneous rocks, and problems of chemical geology.

ROBERT WALPOLE ELLIS, professor of geology at the University of New Mexico for 19 years and state geologist of New Mexico from 1918 to 1927, died March 10 at the age of 68.

SIR ALBERT KITSON, geologist, died on March 8, in Baconsfield, England. He was 69 years of age.

MARK L. REQUA, mining engineer, civic leader, and California representative on the Republican National Committee, died in Los Angeles on March 6 at the age of 70.

ERRATA.

Vol. XXXII, No. 1, p. 90, footnote no. 21 should read Zavaritsky instead of Lavaritsky.